THE SIGNIFICANCE OF TROPICAL CYCLONE RAINFALL IN THE WATER SUPPLY OF SOUTH FLORIDA

BY

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Dedicated to Pam, Mom, Dad, Adam, and Fred.

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Hurricanes and tropical storms are an important part of the hydrologic cycle in South Florida. Although these storms may cause damage to coastal properties and endanger lives, they also bring rainfall to recharge water supplies. If hurricanes fail to influence the rainfall of this region, either because of human intervention by weather modification or because of possible natural climatic change, the water budget is affected.

The study of tropical cyclone rainfall for a sixty-year period from 1919 through 1978 reveals that the amount of rain from hurricanes has declined significantly in the last several decades. This decline is discussed in relation to its effects on water supply and management in the South Florida Water Management District. Although declining supplies and increasing consumption portend severe chronic

water shortages in the region, the knowledge that hurricanes do not bring as much rain as water management officials had thought should allow more effective use of surface storage reservoirs.

CHAPTER I

INTRODUCTION AND DEFINITION OF PROBLEM

> "Water supply, with everything these words imply in relation to land use, population growth, agricultural expansion, and maintenance of environmental quality, is a major issue in South Florida." William B. Storch, Chief Engineer, Central and Southern Florida Flood Control District (1973, p. 1).

Water is a vital natural resource. It is necessary for human existence and is used in large quantities in our society. In Florida, water is usually obtained by pumping it from a river or lake or from a well which penetrates an aquifer. Both surface and ground sources are replenished by rainfall which may occur at places quite distant from the eventual pumping site. Rainwater which falls in the interior of the state usually flows toward the coast. Surface flow in rivers to the Gulf of Mexico and Atlantic Ocean is easily observable. Within the ground, however, the water also flows toward the coast. This underground flow from the interior of the peninsula to the coastal zone provides a source of fresh water for coastal area wells and protects aquifers from the osmotic encroachment of salt.

As populations grow, their need for water increases. The population of Florida tends to be concentrated along the

coast where fresh water supplies are least plentiful. Salt water intrusion into depleted aquifers is a problem for many communities and urban wellfields must frequently be moved further inland to find new sources of fresh water.

The same communities which suffer osmotic salt intrusion also face the possibility of severe damage to property and loss of life from tropical cyclones between June and November. The effects of these violent seasonal storms, however, are not entirely maleficent. They bring rain to replenish the water supply even though they may destroy shops and homes.

Tropical Cylones

A cyclone is an atmospheric circulatory system in which the winds rotate into a low pressure vortex. In the Northern Hemisphere, this circulation is counterclockwise, while in the Southern Hemisphere it is clockwise. The term "tropical cyclone" refers to such a circulation which develops over tropical waters. Tropical cyclones are storms in which the energy to drive the circulation is derived from the latent heat of condensation of water vapor. They are distinguished from extratropical cyclones which are driven primarily by the contrasts of temperature and moisture typically associated with cold and warm fronts (Neumann et al., 1978).

Cry (1967) has stated that no other type of atmospheric circulation has a greater variety of form, structure, and movement than tropical cyclones, and that they undergo radical changes of structure and associated weather from the time they form over warm tropical waters to when they dissipate or become modified over land or colder water. Alaka has described the developmental phases of tropical cyclones as follows:

> The weakest stage is the "tropical disturbance" in which rotary circulation is slight or absent at the surface, but possibly better developed aloft. There are no closed surface isobars and no strong winds. Disturbances of this type are common in the tropics. Next in intensity is the "tropical depression" which is associated with one or more closed surface isobars and with sustained winds equal to or less than Beaufort force 7 (32-38 miles/h). When the winds are Beaufort force 8-11 (39-72 miles/h) we have a "tropical storm". Finally, the strongest stage, with winds of Beaufort force 12 (73 miles/h), is the "hurricane." (Alaka, 1968, p. 1)

Although the term "tropical cyclone" may be used to refer to storms of varying intensity, ranging in wind speeds from below force 7 to greater than force 12, it is used in the present study to indicate only those storms with force 8 winds or greater. Such disturbances have been defined by Alaka as tropical storms and hurricanes. This usage is consistent with that found in meteorological literature.

The structure of a tropical cyclone has been described by Riehl (1963) as that of a simple heat engine. First, convergence of surface air toward the center of the storm is initiated by relatively low atmospheric pressure in that

region. Secondly, when air arriving at the storm center begins to rise, it cools owing to reduced pressure at higher altitudes. When rising air is cooled below its dewpoint, clouds form and latent heat of condensation is released from the water molecule into the atmosphere. Release of latent heat at certain places within the storm enlarges the temperature and pressure differentials found between its different parts and levels, and thus provides impetus for more convergence of surface air toward the storm center.

The difference between the low central pressure in a tropical cyclone and the relatively higher atmospheric pressure surrounding the storm, provides great enough temperature gradients to raise the cyclone to tropical storm intensity, but is not sufficient to make the storm develop into a hurricane. According to Malkus (1957), the formation of the so-called "eye" is instrumental in achieving hurricane-force winds. When warm air in the center of the storm begins to descend instead of rising, the increase in atmospheric pressure at lower altitudes causes the air to become significantly warmer than it would be if released latent heat of condensation were the only mechanism. This descending air in the center of the storm thus explains both the relatively calm weather associated with the eye of a hurricane and the very violent conditions which prevail immediately adjacent to it.

Tropical cyclones form over large bodies of warm water and are common to all tropical oceans except the South

Atlantic (Niddrie, 1964). During their early stages in tropical latitudes, they tend to travel from east to west with the easterly winds. Later, they may recurve poleward and thence toward the east under the influence of mid-oceanic high pressure cells and prevailing westerly winds of the middle latitudes (Dunn, 1967).

Destructive Effects of Tropical Cyclones

The damage which tropical cyclones can cause is widely recognized and often the subject of scientific inquiry. The seriousness of the threat of hurricanes to life and property is such that the National Oceanic and Atmospheric Administration (NOAA) maintains a center in Miami, Florida, devoted exclusively to hurricane research.

The danger of tropical cyclones is as well known to the general public as to the scientific community. Editors for newspapers, television, and radio, always seeking sensational stories, are eager to proclaim "devastation" and "disaster" when a hurricane makes landfall. The reading public has been further educated by the best-selling novel, Condominium (McDonald, 1977), which vividly and accurately portrays the type of disaster that could result from a severe hurricane making landfall along the southwest coast of Florida.

Modification of Hurricanes

The popular notion that the role of hurricanes is only destructive has prompted scientists to consider numerous schemes to weaken or divert them as means of preventing or reducing damage. To date these schemes have consisted primarily of physical experiments based on the ability of certain powdered particles to nucleate moisture and release latent heat into the storm system.

Cloud seeding with silver iodide has been attempted on several occasions (Braham & Neil, 1958; Simpson, Ahrens, & Decker, 1963; "Science--Meteorology," 1963; Simpson, J., 1967; Simpson, R.H., 1969; "Project Stormfury . . . ," 1971; NOAA, 1971a). Carbon dust, dropped from an airplane, has been used to interrupt solar radiation above a hurricane (Gray, 1973). Proposals have also been made to apply films of various types to the ocean surface in order to reduce evaporation and interrupt the hurricane's supply of moisture and heat (Kazmann, 1972; Wilson, 1973). Obvious problems of maintaining the integrity of a film on a stormy ocean surface and pollution remaining after the storm have, however, prevented actual experiments with water surface films in hurricanes.

Weakening and diverting tropical cyclones is, of course, well intended, but, as in any instance of attempted environmental modification, may not always lead to an entirely favorable outcome. The solution to one problem

often leads to others. If, for example, a nuclear device were to be used to stir local areas of the ocean, bringing cool water to the surface and thereby removing the hurricane's main energy source, obvious auxiliary damage would be caused by the explosion. The marine environment would be severely affected and land areas would be subject to radioactive rain, making that procedure clearly an unattractive solution to the hurricane problem.

Another proposal for utilizing nuclear devices to control hurricanes is the detonating of a bomb within the storm in order to disrupt its circulatory organization. Unfortunately, this procedure would require a device of such immense power that the bomb would do far more damage than the hurricane would have done if left alone. According to one authority, it has been shown that, "A mature hurricane of moderate strength and size releases as much condensation heat energy through its cloud systems in a day as the nuclear fusion energy of about 400 20-megaton hydrogen bombs" (Simpson & Simpson, 1966, p. 1045).

Problems of Successful Tropical Cyclone Modification

The possibility of modification causing increased damage is obvious and usually addressed at least implicitly in any literature which discusses means for suppressing hurricanes. It is usually assumed that continued research will eventually result in a dependably safe means of

suppressing the great storms. That assumption may be correct insofar as direct damage from the storm is concerned, but it does not take into account the fact that adverse consequences may result even from completely successful attempts to suppress tropical cyclones.

If hurricanes were artificially dissipated at sea or diverted away from land areas, precipitation falling in the areas which would have been in the storms' paths would presumably be reduced. This loss of rainfall could be significant for inhabitants of a hurricane-prone region. Hurricanes and tropical storms are part of the hydrologic cycle in certain tropical and subtropical areas such as the Caribbean Basin and Florida. Water supplies in those regions may be significantly affected by the occurrence or non-occurrence of hurricanes.

The spectacle of the hurricane's immediate fury and the damage resulting from flooding and high winds overshadow the fact that life-giving rain also comes with the storm. The hurricane's rain may remain in the ground, recharging aquifers, for years after the storm's damage has been repaired. Although hurricane damage may be intense in some localities, beneficial rainfall is widespread. The dangers that coastal areas face in the event of a major hurricane are obvious. The problems caused by preventing hurricanes and thereby losing their rainfall are much less obvious, but may in fact be more severe.

Hurricane modification may never become feasible but it is still necessary to consider what might happen if hurricanes fail to arrive, for the simple reason that they are already striking Florida much less often than they did in the past. This may be a cycle that will reverse itself in the 1980's or it may be part of a longer term trend, but what is clear is that relatively few hurricanes have hit the Peninsula of Florida during the last thirty years. Regardless of what causes a decrease in hurricanes, it still affects the water budget, so it is imperative to understand the importance of hurricanes as a source of terrestrial water.

Importance of Tropical Cyclone Rainfall

Economic development and population increase in Florida are mainly concentrated along the east and west coasts of the peninsula. Every major city in South Florida is located in the coastal zone. Coastal populations depend upon rain falling many miles inland for their water. The demands thus placed on coastal aquifers in Florida already exceed locally sustainable supplies. If Florida were deprived of hurricane rainfall, shortages of fresh water in coastal areas could become even more acute. Although damage potential from hurricanes is quite considerable in the coastal zone, it may become relatively unimportant if severe chronic water

shortages affected local economies and population-carrying capacities.

Impacts on interior regions, as well as the coastal zone, must also be considered. Storm tides penetrate inland only a few miles, with the height of the surge dissipating one to two feet for each mile traveled over a flat surface (NOAA, 1976). Hurricane-force winds likewise persist only a few miles inland. For example, the maximum sustained winds of "Carla," 1961, an unusually intense hurricane, decreased from 175 mph at landfall on the Texas coast to less than 75 mph by the time the storm center had traveled 15 miles inland (Friedman, 1975). Lesser storms will carry hurricane force winds lesser distances inland. The eye of Hurricane "David," 1979, traveled along the entire eastern coast of Florida and then impinged on parts of Georgia and South Carolina, but very few places, even along the barrier islands of those three states, experienced winds greater than 50 mph (NOAA, 1979). In contrast, the rain resulting from "David's" influence covered the entire peninsular portion of Florida and penetrated hundreds of miles inland into several neighboring states. A former director of the National Hurricane Center has stated that, "Most hurricanes that cross a coastline drop the major portion of their rain at inland stations after winds diminish below hurricane force" (Simpson & Simpson, 1966, p. 1047).

Although tropical cyclones are both large and violent, the area of extremely violent weather associated with such

a storm is small compared to the area in which rain is stimulated by the disturbance. A given location may frequently experience rainfall and unsettled weather resulting from hurricanes, but rarely be exposed to hurricane-force winds.

Public Concern For The Environment

During the last two decades, concern for the environment has become a popular theme in the United States, prompting the passage of numerous legislative bills by the federal government as well as by many states. Foremost of these laws is the National Environmental Policy Act of 1969 (NEPA). This Act requires that Environmental Impact Statements (EIS) be filed for all major federal actions significantly affecting the quality of the human environment (U.S. Congress, 1970). Although some criticism may be leveled at NEPA for delaying projects and increasing their expense, the law serves the much needed purpose of requiring that the environment be taken into account in making decisions which will affect it. Federal courts have given NEPA a broad interpretation and have applied its mandate strictly (Krupensky & Weismantel, 1979).

The EIS requirement can be used as an effective instrument for protecting the public from adverse consequences developing from suppressing hurricanes. It may, however, be left to an outside party to point out the

problems of loss of rainfall associated with successful hurricane suppression. The existing EIS for the experimental Project Stormfury ignores this issue. Prepared by the Weather Modification Division of NOAA it states, "There is no evidence at this time that any adverse effects have occurred or may be expected to occur as a result of these experiments" (NOAA, 1971a, p. 3). The present research addresses the matter of how much water comes from hurricane rainfall and provides some of the information that would be needed to produce a more comprehensive evaluation of the impact of hurricane modification or natural climatic change that causes the amount of rainfall from hurricanes to decline.

CHAPTER 2

LITERATURE CONCERNING THE BENEFICIAL ASPECTS OF HURRICANES

There is a very large body of literature concerning hurricanes. Most of it, however, concerns their destructive effects and the means to cope with those effects. Beneficial aspects are rarely discussed at length. Tannehill (1952), one of the few writers to comment on "tropical storms that are beneficial," devotes only one page to that topic in a 308-page book. He states:

> Not all tropical cyclones are destructive: in fact many of them are beneficial. Rains accompanying them revive crops and replenish supplies of storage water. Even in the most destructive hurricanes, areas some distance from the storm center, where winds are not dangerous, receive beneficial rains. (Tannehill, 1952, p. 130)

Although Tannehill was one of the most knowledgable experts of his time on the topic of hurricanes, he offers only two rather dated references to support his statement. Drawing from Fassig (1929) Tannehill comments:

> . . . 60 percent of the storms that affected Puerto Rico from 1899 to 1928, inclusive, were beneficial. Only 10 percent were overwhelmingly destructive, while 30 percent were locally destructive but beneficial in some parts of the island. In the majority of Puerto Rican hurricanes during this period, losses caused by the winds of the storm were insignificant compared with the great benefits to crops and municipal water supplies. (Tannehill, 1952, pp. 130-131)

Tannehill's other reference is Visher (1922). Visher makes only a brief comment that the rains brought by hurricanes are "often very welcome." Further reading of Tannehills's book, however, reveals another benefit which may result from hurricanes. On several occassions when fruit trees have been stripped of their leaves by high winds, the trees have reblossomed and produced a second crop of fruit.

Bowden (1974) also devotes a small part of a book-length monograph to the beneficent hurricane. He was apparently surprised when two long time residents of St. Croix "pointed out that hurricanes brought welcome rain to the islands." Bowden states that:

> This conception of the beneficent hurricane is surprising, at first glance. But it must be remembered (1) that the cautious scholar R.B. Stone wrote in 1942 "that it is not minimizing the danger from these storms to say that they rarely strike with great severity," and (2) that many if not a majority of the hurricanes that have come within 100 miles of the islands in the last 100 years have brought copious rains, frequently to parched agricultural lands. . . . there is a strong possibility that the 48 known hurricanes that have passed over or close to these dry islands (Virgin Islands) in the last 100 years may, on balance, have been more beneficial than detrimental. (Bowden, 1974, p. 72)

Bowden offers no systematically acquired evidence to support the concept of the beneficent hurricane and cites only one literary source concerning the topic, the aforementioned book by Tannehill. He further states that it is a "minority view" and that his informants were "not old

enough to have experienced the last major hurricane of 1928 on St. Croix" (Bowden, 1974, p. 72).

Sugg (1968) has examined the rainfall data from tropical cyclones which have moved over drought-stricken areas and has provided numerical evidence of the beneficence of hurricane rainfall. Although he establishes that hurricane rainfall may be of great value in ameliorating drought, he fails to observe that it may be a part of the normal water supply for an area. Sugg states, "It is quite obvious that rains, to be most beneficial, must fall on drought-stricken areas" (Sugg, 1968, p. 39).

After presenting a well documented case in order to demonstrate the benefits of hurricane rainfall, Sugg goes on to mention briefly several other supposed benefits. Although his approach to the "other benefits" is less scientific than his treatment of rainfall, his comments draw attention to the wide variety of impacts which a hurricane may generate. Sugg's "other benefits" are 1) abnormal migrations of fish and crustaceans, resulting in larger catches for commercial fisherman, 2) destruction of slum areas, 3) suppression of rodents and insects by damaging their breeding grounds, and 4) influencing historical events by sinking warships.

It is arguable whether the effects of hurricanes mentioned by Sugg are actually beneficial. Abnormal migration of fish and crustaceans may be accompanied by higher than normal mortality rates. Destruction of slum

areas deprives poor people of homes. Destruction of rodent and insect breeding areas in one place is probably accompanied by their replacement elsewhere. The evaluation of whether historical events have been influenced favorably or unfavorably depends very much upon the background of the observer. Although Sugg has titled his article "Beneficial Aspects of the Tropical Cyclone," he has demonstrated no definite benefit other than the cessation of drought.

An earlier article by Sugg (1967), although not directed primarily at the beneficial aspects of the tropical cyclone, is more effective in demonstrating an unexpected gain resulting from a hurricane. In his study of the "Economic Aspects of Hurricanes," he has observed that short term booms have been recognized as a result of insurance compensation in hurricane disaster areas in the United States.

An example of a short term economic gain resulting from a hurricane strike is given by Parades (1978). While studying citizen responses to Hurricane "Eloise," 1975, in Panama City, Florida, Paredes encountered the proprietor of a beachside tavern, who told of throngs of construction workers who frequented his establishment during the clean-up and rebuilding following the storm. Paredes' study revealed that the tavern operator was not the only person to benefit from the storm. Thirty percent of the respondents to his survey expressed the opinion that Hurricane "Eloise" had beneficial effects on the local economy.

Short term increases in spending have also been observed immediately before a hurricane strikes. Anderson (1972) has stated that hurricane warnings cause people to take actions to prepare for the storm. Those actions often consist of purchasing items which are perceived to be useful during a hurricane, thus certain businesses will experience brisk sales as a result of the hurricane warning even though the storm might not in fact strike that locale.

Weaver (1968) has written about a variety of benefits which may be derived from hurricanes. Favorable developments which Weaver cited as resulting from hurricanes include: (1) Sugg's observation of short term booms resulting from insurance compensation, (2) rainfall, and (3) increased rate of economic development and improvements to resource management. The third item referred specifically to events which occurred on the island of Grenada after Hurricane "Janet," 1955. Weaver showed that the storm's damage caused the Forestry Department and Fisheries Division to be created and the Department of Agriculture to be revitalized. Furthermore, he stated that the hurricane initiated improvements in transportation and communication facilities and a shift from nutmeg and cacao to more lucrative bananas as the principal export.

The body of literature concerning the beneficial aspects of hurricanes is small, but even the few works cited here indicate the diversity of favorable results which a hurricane may generate. Much of what is said in

the cited works is of a speculative nature and very little is supported by thorough scientific inquiry. The need for further research concerning non-destructive aspects of hurricanes is clearly justified by the paucity of existing literature pertaining to that topic and its speculative character.

CHAPTER 3

HURRICANE SUPPRESSION

Damage Caused by Hurricanes

In the continental United States from 1925 to 1970, hurricanes were responsible for 4911 deaths and the destruction of $7.5 billion in property (Brinkman, 1975). Compared to other natural hazards, hurricanes rank second in both the number of fatalities and value of property damage.* The harmful effects of hurricanes are further emphasized by their concentration in a narrow zone along the coastlines of the Atlantic Ocean and the Gulf of Mexico.

Historical records bear witness to the damage which can result from severe hurricanes. A storm tide which inundated Galveston, Texas, in 1900 is said to be responsible for the loss of 6000 lives. In 1909, 350 lives were lost to a storm in Louisiana and Mississippi. In August and September of 1915, separate hurricanes struck Galveston, Texas, and Burwood, Louisiana, each causing the loss of approximately 275 human lives. Similar losses of life are reported for

*Tornadoes killed 8037 people during the same time period, and floods caused $9.2 billion in damages from 1925 to 1969 (Brinkman, 1975).

storms of 1919 and 1926 in Florida. Over 1800 persons are estimated to have died in the September 1928 hurricane in which wind-driven waters from Lake Okeechobee overflowed into populated areas. Over 400 persons are known to have perished in the "Labor Day Storm" of 1935 in the Florida Keys and along the Gulf of Mexico coast to Tampa. Hurricane "Audrey" in 1957 took 390 lives. In more recent years, deaths in the United States have been fewer, owing to advance warning and evacuation of people from exposed locations, but property damage continues to grow as a result of increasing urbanization (NOAA, 1971b) in areas where building codes and land use controls do not effectively minimize hazard risks.

Brinkman's summary of hurricane hazards in the United States indicates how rapidly population and urban development are increasing in areas subject to hurricane violence. Dury (1977) has further warned that past estimates of the danger from hurricanes are probably too low. His application of statistical techniques to data derived from hurricanes occurring from 1900 through 1972 yields results which prompted him to forecast that: "Prospects for hurricane-related flood damage in a single event within the next quarter century appear to be grim indeed" (Dury, 1977, p. 257). It is little wonder that men seek to suppress these great storms.

Cloud Seeding

A variety of techniques for suppressing hurricanes are available. Suggestions which include the use of nuclear devices are so obviously infeasible that no actual experiments have been performed using those means, and relatively little research regarding evaporation suppression or blocking of insolation has been performed. The single means for suppressing hurricanes which is most frequently studied by scientists and discussed by the public at large is cloud seeding.

Cloud seeding is accomplished by artificially applying certain finely particulated materials to potential rain clouds or clouds already producing rain. This procedure is an outgrowth of Langmuir's (1947) studies of the role of nuclei in creating droplets of water from clouds. Most commonly silver iodide, and occasionally dry ice or other substances, are spread into clouds to increase the number of available hygroscopic nuclei. It is hypothesized that this practice should increase the quantity of rainfall derived from a given cloud. Opinions about its effectiveness vary and research concerning the efficacy of cloud seeding as ameans of increasing long term rainfall has not yet yielded conclusive results (Kazmann, 1972).

In hurricane seeding, the goal is not to increase precipitation but rather to modify the storm so as to reduce its intensity or to cause it to move in a direction away

from populated areas (Braham & Neil, 1958). Seeding of selected portions of the hurricane is used to decrease the temperature and pressure differences within the storm and thereby disorganize circulation around the eye and reduce wind speeds ("Project Stormfury . . . ," 1971).

The first hurricane cloud seeding experiment on record occurred off the coast of Georgia and South Carolina in 1947. A group from Project Cirrus, a rainmaking experiment, flew into the storm and dropped about 180 pounds of dry ice. Unfortunately, the storm changed direction immediately after the seeding and made landfall at Savannah, Georgia, causing heavy flooding and considerable damage to property in Georgia and South Carolina (Braham & Neil, 1958; "Science--Meteorology," 1963; Niddrie, 1964; "Project Stormfury . . . ," 1971).

The sudden change in direction of the 1947 storm was at the time cited as evidence that the seeding had had a marked effect. However, inasmuch as previous and subsequent storms have exhibited equally erratic changes in path without having been seeded, no definite conclusion may be drawn from the events following that particular seeding episode (Braham & Neil, 1958). At present, it seems unlikely that the 1947 seeding experiment had a significant effect upon the hurricane. R.H. Simpson (1969), while he was director of the National Hurricane Center, commented that for seeding to be effective, it would have to be performed continuously, rather than on a single application basis.

No further hurricane cloud seeding was attempted until 1961. At that time the United States Weather Bureau authorized the dropping of silver iodide into Hurricane "Esther." Maximum wind speeds in the seeded sector dropped by as much as 14 percent. Within hours after the seeding, however, the storm had regained full strength ("Science--Meteorology," 1963).

During the following year, Project Stormfury was established as a collaborative effort by the Departments of Commerce and Defense. The express roll of Project Stormfury is to perform research pertaining to hurricane modification (NOAA, 1971a). This project is part of a larger effort aimed at several aspects of research pertaining to hurricanes. J. Simpson (1967) has described the areas of major concentration of hurricane research. Little change has occurred since her remarks:

> No effort is currently being directed towards operational weather modification, which is still largely in the empirical or statistical phase. The current work consists of background experiments, in the following three senses of the word:
>
> 1. "Before and after" measurements on full-scale atmospheric systems after introducing an artificial alteration. The alteration is designed to be predictable and controllable, and is at least backed by physical hypotheses outlining its consequences. Our Stormfury cumulus and hurricane seeding experiments are examples.
>
> 2. Detailed observations upon situations in which nature herself is performing a partially controlled experiment. An example is our study of the alterations of airflow and convective cloud patterns

> by heated islands. The measurements can be examined in the framework of a fairly well developed theoretical model.
>
> 3. Numerical experiments based on solutions of the hydrodynamic equations and comparing the results with aircraft and other observations.
>
> We hope also, when staff permits, to embark on some laboratory experiments. (J. Simpson, 1967, p. 95)

Cloud seeding experiments are the most highly publicized hurricane research activity, although very little seeding has taken place. The first hurricane to be seeded under the auspices of Project Stormfury was "Beulah," 1963. After "Beulah," there was not another hurricane seeded until "Debbie," 1969 (NOAA, 1971a; "Project Stormfury . . . ," 1971). The seeding of Hurricanes "Esther" and "Beulah" were very similar. Silver iodide was dropped along the eye wall of each storm and winds diminished for several hours afterward as apparent results of the seeding. "Debbie" was more heavily doused with silver iodide than were the previous storms, as well as receiving the treatment further out in the cloud wall, with the apparent consequence of having greater effect upon the storm ("Project Stormfury . . . ," 1971).

The apparent success of the experiment with Hurricane "Debbie" suggests that hurricane modification through cloud seeding can be made into a feasible routine practice. In R.H. Simpson's (1969) words:

> The changes that occurred in Debbie were these: The diameter of her eye had originally been about 15 miles. Reports received at the

> National Hurricane Center from aircraft monitoring the storm indicated that, after the seeding, the eye wall expanded to a 40-mile diameter. The central pressure rose an appreciable amount--which indicates a lessening of intensity--and maximum winds decreased somewhat. It was not a spectacular change, but it was a change essentially in the direction that was predicted by the hypothesis on which we were operating. (R.H. Simpson, 1969, p. 35)

"Ginger" in 1971 is the only other hurricane which has been seeded under the Project Stormfury program (NOAA, 1978). The results of seeding "Ginger," however, were not as promising as those of "Esther," "Beulah," and "Debbie." Wind speeds in Hurricane "Ginger" actually increased after seeding (NOAA, 1972).

Unpredictability of Hurricanes

The unpredictability of hurricanes and uncertainty about how they will react to seeding have been major factors which have limited the number of hurricane modification experiments. Fear of law suits has prompted the administrators of Project Stormfury to be very selective in choosing a hurricane to seed ("Science--Meteorology," 1963).

Statements made by Frank (Malone, 1979), in his capacity as Director of the National Hurricane Center, during Hurricanes "David" and "Frederic" in 1979 illustrate the inability even of hurricane experts to forecast accurately the storms' movements and development. Dr. Frank predicted on September 2 that the eye of Hurricane "David"

would come ashore during early morning hours of September 3, somewhere between Palm Beach, Florida, and Marathon, Florida. The eye of the storm actually crossed the coast slightly north of Palm Beach, just outside the predicted zone, after noon on September 3. When asked about the apparent incorrectness of his forecast after the storm's eye missed the center of the predicted zone of landfall by 100 miles, Frank commented that his forecast, "was about as close as we can get. . . . My average forecast is plus or minus 100 miles" (Malone, 1979, p. 1).

The "plus or minus 100 miles" degree of accuracy applies only to very short term forecasts. When the forecast concerns an event more than 24 hours into the future, accuracy drops sharply. Predictions of the movement and development of a hurricane are based upon the observation that although the path of the storm may sometimes be quite erratic, changes in the direction or intensity of a hurricane do not usually occur rapidly. The forecaster may generally assume that the direction and intensity of a hurricane will continue with little change for a short while. Although research is expanding the available knowledge of atmospheric dynamics, the physical properties of the atmosphere are not yet sufficiently understood so as to provide any more dependable guidelines for hurricane forecasts than the projection of current trends and movements.

On September 7, several days after Frank's "as close as we can get" estimate of "David's" landfall, he rendered his opinion concerning the seriousness of the storm called "Frederic." At that time, "Frederic" had just crossed the island of Hispaniola and had weakened to a level of intensity which barely qualified it as a tropical storm. Frank proclaimed that "Frederic" posed no serious threat. Other persons connected with the National Hurricane Center were quoted as saying, "I would not encourage people to keep their storm shutters up just because of Frederic." and "The center is very weak and diffuse" (Dominican Republic . . . ," 1979, p. 12). Less than a week later, 340,000 people evacuated from coastal areas of Florida, Alabama, and Mississippi as "Frederic" approached with 130 mile per hour winds and 15-foot storm tides (Markowitz, 1979).

The prevailing lack of detailed knowledge concerning the mechanisms which control hurricanes has led to the criticism that actual experiments in cloud seeding are premature. Only four years prior to the official advent of Project Stormfury, a study funded through the National Hurricane Research Project (Braham & Neil, 1958) stated that,

> It appears to the writers at this time that the hurricane is so poorly described and that there is so little known about the thermodynamic and hydrodynamic processes which govern its growth and decay, it is not possible to set down a rational argument linking any known effect of seeding to predicted changes in the behavior of the storm. (Braham & Neil, 1958, p. 2)

Simpson & Simpson (1966) have responded to that criticism by comparing hurricane modification research with early research concerning nuclear physics:

> It has been stated that one should know more about hurricanes, be able to model any experiment numerically using the hydrodynamic equations, and be able to validate the assumptions before field experiments are undertaken.
>
> This has not been the approach of the classical physicist, for whom the early atomic pioneers such as Rutherford and Bohr will serve as familiar examples. These men chose to learn about atomic structure by conducting experiments upon actual atoms--this is our example and motivation in hurricane experimentation. (Simpson & Simpson, 1966, p. 1045)

The Simpsons' analogy may be used equally well as an argument in support of the opposing sentiment. Early nuclear physicists cannot have imagined the immensely destructive forces with which they were dealing. The consequences of accidently detonating a nuclear explosion in a laboratory placed in some large city are obvious and should provide an insight to the possible consequences of tampering with nature's greatest storms. By the Simpsons' own admission, a mature hurricane releases many times the quantity of energy released by the typical hydrogen bomb.

The first hurricane cloud seeding experiment occurred in the same year the Langmuir's theory of raindrop nucleation was published. Although the question of whether seeding experiments are still premature may be subject to debate, there is no doubt that the 1947 seeding experiment was highly exploratory. Much too little was known about the

dynamic aspects of hurricanes at that time and too little caution was exhibited in the venture. Since 1947 great strides have been made in improving the understanding of hurricanes. Some of that new knowledge has been derived from cloud seeding experiments. The sum of what is known about hurricanes is, however, still small compared to what is unknown and, all too often, persons who are in position to make decisions concerning the modification of weather must act on the basis of sketchy information.

CHAPTER 4

RESEARCH DESIGN

The importance of hurricane and tropical storm rainfall, as part of the total rainfall of South Florida, is measured and the impact that the loss of such rainfall would have on South Florida's water supply is evaluated. The principal questions addressed herein are stated below. Each question is answered in the order stated so that the information derived from earlier inquiries may be used in answering later questions.

I. What quantities and proportions of South Florida's rainfall come from hurricanes and tropical storms?

II. What quantities and proportions of hurricane and tropical storm rainfall are retained as part of South Florida's water supply?

III. What effects would the loss of hurricane and tropical storm rainfall have on South Florida's long term ability to meet water demands?

IV. What implications would the effects of deleting hurricane and tropical storm rainfall from the water supply have for long range water management planning in South Florida?

Study Area

The study area is the South Florida Water Management District (SFWMD) (Figure 1). This region is chosen because hurricanes strike here more frequently than any other part of the state. Both negative and positive impacts of hurricanes are greater for this region than elsewhere. South Florida, particularly the southeastern coastal area, which is exposed to direct hurricane strike from the sea, is highly urbanized. This means not only that thousands of people and much valuable real estate face potential danger from hurricanes, but also that there is a high demand for water for municipal supplies and thermal electricity generation. Inland from the coastal cities, extensive areas of agriculture and natural wetlands also require water. Although South Florida could have much to gain if hurricanes did not strike, it could also have much to lose. The hurricane is a prominent part of the hydrologic cycle in this region.

Organization and Methodology

1. What quantities and proportions of rainfall result from hurricanes and tropical storms in the South Florida Water Management District?

Two types of information are used to answer this question: A) What is the total amount of rainfall which

FIGURE 1

THE SOUTH FLORIDA WATER MANAGEMENT DISTRICT

occurs? and B) How much rainfall comes from tropical cyclones? After each of these measurements is acquired, the figures are paired and used to calculate the percentage of rainfall from hurricanes and tropical storms.

II. What quantities and proportions of hurricane and tropical storm rainfall are retained as part of the South Florida Water Management District's water supply?

Estimates of the amounts of infiltration and impoundable runoff are based upon the rise of water levels in test wells and the area of impoundment basins and their watersheds.

III. What effects would the loss of tropical cyclone rainfall have on the South Florida Water Management District's ability to meet its water requirements?

Several types of information are required to answer this question. A) What effects would the loss of hurricane rainfall have upon long range water supplies? This is obtained by comparing rainfall from a 30-year interval of high hurricane activity with rainfall from a 30-year interval of low activity. B) How much water is used in the Water Management District? These data are obtained from published documents. C) What will the water demands for the future be in the Water Management District? Estimates of future demand are based on projections of past water use rates and population growth.

IV. What implications would the effects of deleting hurricane and tropical storm rainfall from the water supply have for long range planning in the South Florida Water Management District?

The plans and policies of the South Florida Water Management District are examined with respect to actions that may be affected by a decline in rainfall. Recommendations are made regarding indicated changes in water management policies.

CHAPTER 5

TROPICAL CYCLONE RAINFALL

Data Sources

Information regarding the dates and routes of hurricanes and tropical storms was obtained from various sources. The most useful reference was Neumann et al. (1978) Tropical Cyclones Of The North Atlantic Ocean 1871-1977. This book contains numerous maps illustrating the routes of tropical cyclones and textual descriptions of the geographical and temporal distributions of the storms. Tannehill (1952) Hurricanes contains similar descriptions of tropical cyclone tracks and was also used extensively. Other references which were consulted included Bruun et al. (1962), Coastal Engineering Department, University of Florida (1951), Dunn (1967), Haggard & White (1959), Hebert & Taylor (1978), NOAA (1973), Schoner & Molansky (1956), Simpson (1971), Sugg, Pardue, & Carrodus (1971), and Tannehill (1938).

Forty-one hurricanes and forty-four tropical storms (Table 1) influenced rainfall in the South Florida Water Management District from 1919 through 1978. Rainfall data are recorded for the dates on which the storms influenced

TABLE 1

DATES OF HURRICANE AND TROPICAL STORM RAINFALL

HURRICANES

1919	Sept.	9-10	1945	Sept.	14-16
1920	Sept.	25, 29-30	1946	Oct.	7- 8
1921	Oct.	24-25	1947	Sept.	17-18
1924	Oct.	19-21	1947	Oct.	11-12
1926	July	26-28	1948	Sept.	21-23
1926	Oct.	20-21	1948	Oct.	4- 5
1928	Aug.	7- 9	1949	Aug.	26-28
1928	Sept.	16-17	1950	Sept.	3- 6
1929	Sept.	27-29	1950	Oct.	15-18
1933	July	29 - Aug. 1	1951	May	17
1933	Sept.	1	1959	Oct.	16-19
1933	Sept.	4- 6	1960	Sept.	9-11
1933	Oct.	3- 5	1964	Aug.	26-28
1935	Sept.	2- 5	1964	Sept.	9-11
1935	Sept.	28-29	1964	Sept.	27-28*
1935	Nov.	4- 5	1964	Oct.	5- 6*
1936	July	29-30	1964	Oct.	14-15
1939	Aug.	11-13	1965	Sept.	7- 9
1941	Oct.	6	1966	June	8- 9
1944	Oct.	16-19	1966	Oct.	2- 5
1945	June	21-24	1968	Oct.	16-19

* Hurricane "Hilda", passing and returning.

TROPICAL STORMS

1925	Nov.	30 - Dec. 1	1953	Aug.	27-31
1926	Sept.	15-17*	1953	Oct.	3- 5
1928	Aug.	12-14	1953	Oct.	7-10
1930	Sept.	8-10	1959	June	16-20
1932	Aug.	29-31	1960	Sept.	21-25
1934	May	26-28	1962	Aug.	24-26
1934	July	22-23	1964	June	5- 6
1936	June	13-15	1967	Sept.	7- 8
1936	Aug.	21-22	1968	June	2- 6
1937	July	28-30	1968	June	17-20
1937	Aug.	29-31	1968	Aug.	9-10
1938	Oct.	13-17*	1969	Sept.	6- 7
1940	Aug.	2- 3	1969	Oct.	1- 4
1941	Sept.	15-17	1970	Sept.	13-15
1941	Oct.	17-21	1970	Sept.	26-27
1945	Sept.	3- 5	1971	Aug.	10-12
1946	Nov.	1- 2	1972	Sept.	4- 6
1947	Aug.	19-20	1974	June	24-28
1947	Sept.	22-23	1974	Oct.	6- 7
1947	Oct.	5- 6	1975	June	26-27
1951	Oct.	1- 3	1976	Aug.	17-19
1952	Feb.	2- 3			

* two storms overlapped

Florida and summed to obtain the total rain from tropical cyclones during the sixty-year period and for specified shorter time intervals within that period. Although only rainfall totals and the dates on which the rain fell are needed to calculate how much water originates from tropical cyclones, several other items are tabulated and compared to hurricane and tropical storm rainfall in order to obtain a better understanding of the relative importance of tropical cyclone rainfall as a part of the total rainfall of the area.

In addition to daily rainfall data for the dates on which tropical cyclones were passing the study area, rainfall is also tabulated for each calender year, and for the months of peak tropical cyclone activity from June through October of each year. Although the hurricane season for Florida is officially defined as lasting from June through November, only one hurricane and two tropical storms influenced rainfall in South Florida in November during the study period. This conforms to the findings of Niddrie (1964) for tropical cyclones in the Caribbean Sea and Atlantic Ocean from 1492 to the early 1960's. November is therefore excluded from the hurricane season for the purpose of this study. Rainfall data are obtained from monthly and annual summaries of climatological data published by the United States Government.

Selection of Stations

Although there are numerous stations within and near the study area, few of them have existed for the entire sixty-year period. Only one station, Bartow, a few miles outside of the Water Management District, appears to have remained at exactly the same site for the full sixty years. Key West, another station with sixty years of complete records, and very little change in location, is excluded in spite of being within the Water Management District because rain which falls in the Keys does not contribute to the recharge of mainland aquifers (Spangler, 1981).

After numerous stations had been eliminated because of location, short periods of records, or erratic records, nineteen weather stations were found to be suitable. These stations are Arcadia, Avon Park, Bartow, Belle Glade, Everglades City, Fellsmere, Fort Lauderdale, Fort Myers, Fort Pierce, Homestead, Isleworth, Kissimmee, La Belle, Miami, Moore Haven, Okeechobee, Orlando, Punta Gorda, and West Palm Beach (Figure 2).

Since it was not possible to use only weather stations which had sixty years of continuous data in exactly the same location, a series of t-tests was performed to ascertain the degree of temporal consistency of the data from each station. The sixty-year study period was divided into two thirty-year intervals which were compared as independent samples. The mean annual rainfall at ten of the nineteen

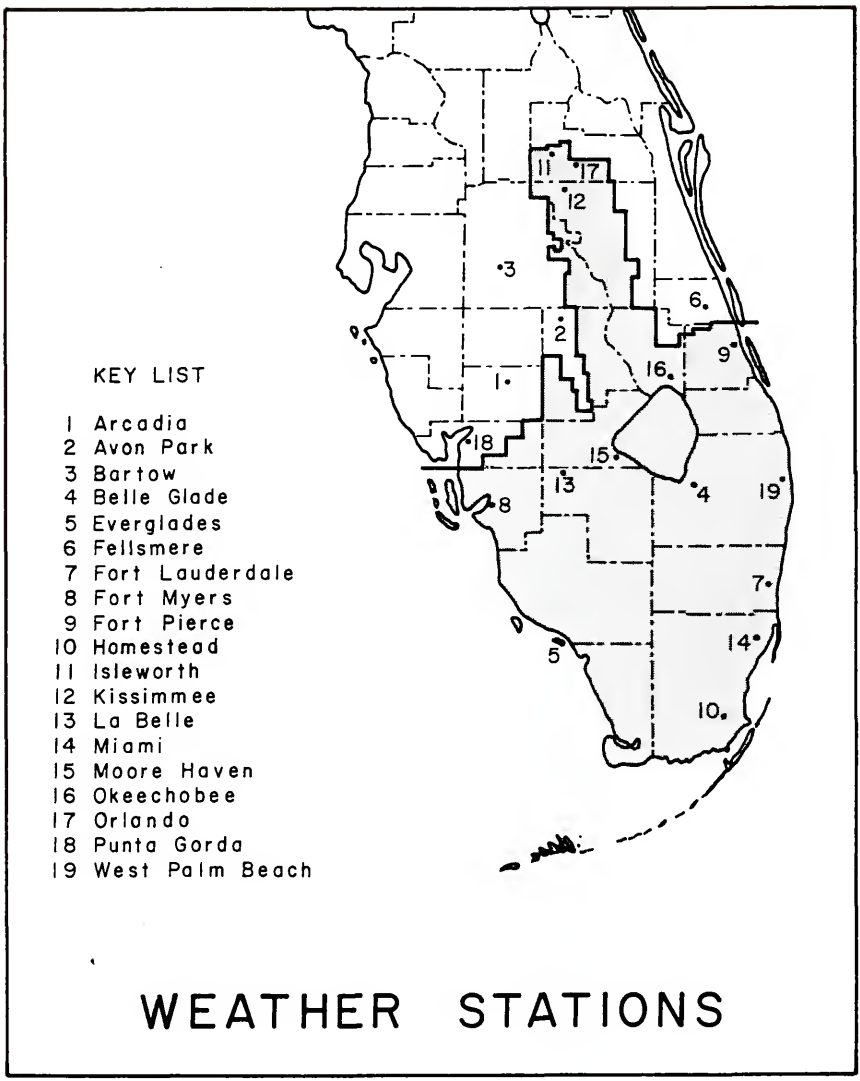

FIGURE 2

WEATHER STATIONS

stations was significantly different for the two intervals at the 95% confidence level (Table 2).

It is noteworthy, however, that Bartow, the station which had the most complete and dependable record for the full sixty-year period, was one of the stations which the t-test indicated as being significantly different from itself. The differences observed between rainfall data from the earlier half of the study period compared to the later half thus do not necessarily indicate that the data were affected by changes in station location. Rather, the differences might be explained by climatic change. Analyses of hurricane rainfall data and total rainfall for the region indicate that significant declines have occurred in the second half of the study period.

Determining if Rain is Caused by a Tropical Cyclone

Rainfall which occurs during the passage of a hurricane or tropical storm center several hundred miles away may or may not be directly related to the passing tropical cyclone. Satellite remote sensing imagery may be used to determine the areal distribution of clouds associated with the tropical cyclone and reveal the areas where rainfall was directly attributable to such a storm, but satellite imagery exists only from 1960 to the present, and even then is difficult to obtain for 1960 through 1968. No such record of the continuity of cloud coverage is available for earlier

TABLE 2

t-TESTS OF RAINFALL DATA--INDIVIDUAL STATIONS

FIRST 30 YEARS VS. SECOND 30 YEARS

CITY	1919-48 MEAN	1949-78 MEAN	t	
Arcadia	52.50	52.28	0.522	
Avon Park	53.52	52.55	2.234	
Bartow	54.77	53.16	3.846	*
Belle Glade	57.12	55.70	3.595	*
Everglades City	53.61	53.40	0.556	
Fellsmere	55.93	51.82	8.991	*
Fort Lauderdale	61.56	59.74	3.901	*
Fort Myers	53.27	53.29	-0.064	
Fort Pierce	52.76	52.34	1.081	
Homestead	62.20	60.41	1.149	
Isleworth	51.60	51.04	1.424	
Kissimmee	49.93	49.24	1.723	
La Belle	51.36	51.74	-1.183	
Miami	57.47	57.51	-0.077	
Moore Haven	49.95	49.33	1.608	
Okeechobee	46.97	45.60	3.726	*
Orlando	51.06	49.89	3.254	*
Punta Gorda	50.96	49.37	3.641	*
West Palm Beach	61.78	59.40	5.919	*

CRITICAL VALUES OF t:
0.05 Confidence Level = 2.04
0.01 Confidence Level = 2.75
* = Significant at .01 Level

TABLE 3

SATELLITE IMAGERY

DATE	STORM	SATELLITE
1969 Sept. 5	T.S. GERDA	ESSA 9
1969 Oct. 2	T.S. JENNY	ESSA 9
1970 Sept. 14	T.S. FELICE	ITOS 1
1970 Sept. 27	T.S. GRETA	ITOS 1
1971 Aug. 12	T.S. BETH	ESSA 9
1972 June 19	HURR. AGNES*	ESSA 9
1972 Sept. 5	T.S. DAWN	ESSA 9
1974 Oct. 6	T.S. (no name)	SMS/GOES
1974 June 25	Subtrop. St. (no name)	SMS/GOES
1975 June 26	T.S. AMY	SMS/GOES
1975 Sept. 23	HURR. GLADYS*	SMS/GOES
1976 Aug. 17	T.S. DOTTIE	SMS/GOES
1979 Aug. 30	HURR. DAVID*	SMS/GOES
1979 Sept. 3	HURR. DAVID*	SMS/GOES
1979 Sept. 8	HURR. FREDERIC*	SMS/GOES
1979 Sept. 12	HURR. FREDERIC*	SMS/GOES
1980 Aug. 5	HURR. ALLEN*	SMS/GOES
1980 Aug. 9	HURR. ALLEN*	SMS/GOES

* Indicates storms which passed either outside of the study area or after the end of the study period.

times. Without direct knowledge of whether an area was covered by clouds which emanated from a tropical system, it is not possible to determine with certainty if rain which fell at a given place on a certain day was the result of the passing tropical cyclone or of other local or extra-tropical causes.

Previous Studies

Previous studies of tropical cyclone rainfall have failed to address the problem of whether a given observation of rain actually resulted from a specific storm. Cry (1967) discusses the problem of wind reducing the effectiveness of rain collection devices but neglects the question of whether the given sample should be considered at all. Goodyear (1968) avoids raw climatological data by using the United States Army Corps of Engineers "Storm Rainfall in the United States" (1945 et seq) whenever possible. For earlier times he draws his information directly from summaries of weather station records, but gives no explanation of how it is known that the rainfall is the result of tropical cyclones in either situation. Examining the Corps of Engineers' storm rainfall reports also discloses no statement on this topic.

Milton (1978) cites Schoner and Molansky (1956) and Miller (1958) as having the most sophisticated networks of data to work with, but it appears that their methodologies for selecting the data to be used were no more advanced than

others who have written on the topic of tropical cyclone rainfall. Schoner and Molansky list the Climatological Data and Corps of Engineers as their data sources, just as Goodyear does, and make no further statement regarding the selection of data.

Miller chose to discontinue tabulating data whenever the winds around the center of the storm dropped below hurricane force. This practice ignores any rain which results from tropical storms and a substantial part of the rain resulting from dissipating hurricanes. Miller also discusses the problems of rain-gauge effectiveness and the possibility of orographic and extratropical influences on hurricane rainfall. He states that hurricane rainfall data from Florida are virtually free of orographic and extratropical effects. While the flatness of Florida certainly minimizes orographic effects, the statement regarding extratropical influences must be questioned. NOAA satellite imagery of Hurricane "Gladys," September 23, 1975 (Figure 3), clearly shows a middle latitude frontal system blending with the tropical cyclone.

Gentry (1964) is the only author who has been found to discuss a means for determining the actual areas in which rain is falling in the vicinity of a hurricane or tropical storm. He cites the use of airborne radar for the purpose of studying the patterns of hurricane rainbands. Gentry's methodology is not relevant to the present project, however, because a source of radar imagery for the appropriate time interval could not be found.

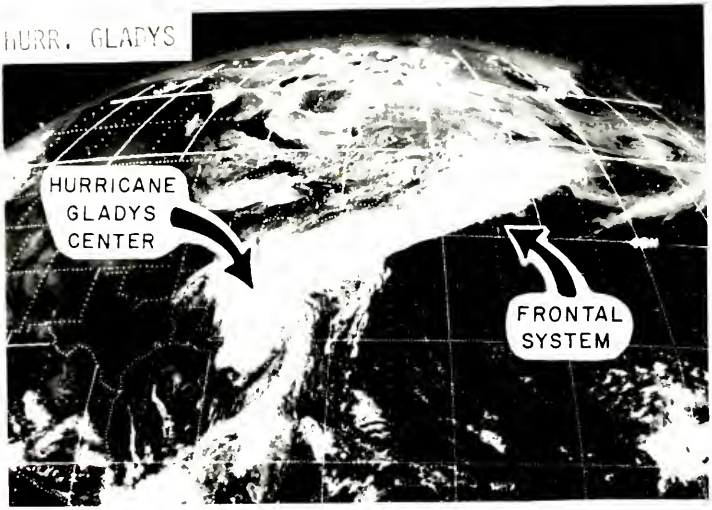

FIGURE 3

HURRICANE "GLADYS", SEPTEMBER 23, 1975

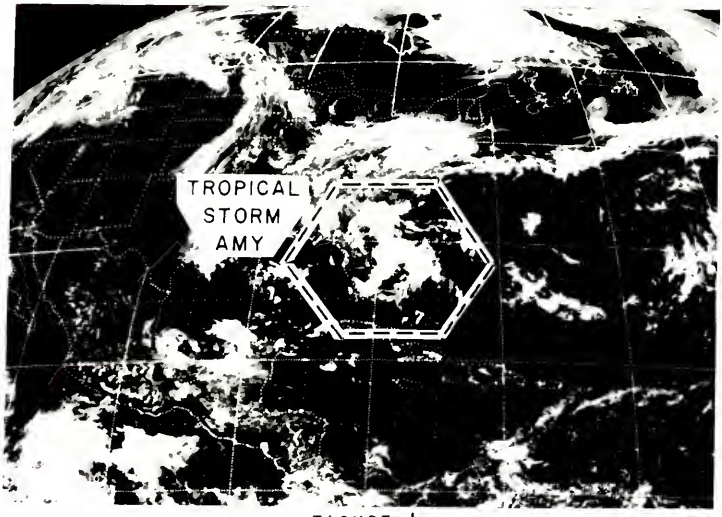

FIGURE 4

TROPICAL STORM "AMY", JUNE 26, 1975

Criteria for Determining Rainfall Source

Remote sensing imagery was employed in this study but was found to be of little use because no hurricanes and only eight tropical storms passed near the South Florida Water Management District between 1969, the time for which the earliest imagery could be obtained, and the end of the study period in 1978. Other means had to be found to determine if rainfall could be attributed to a tropical cyclone.

Several assumptions were tested as reasonable criteria on which to base such decisions. These assumptions were designed to provide a consistent set of criteria which could be applied in the absence of direct evidence. The results obtained by such criteria were compared to the conclusions derived from remote sensing imagery (Table 3). Because of the small number of tropical cyclones covered by satellite imagery during the study period, several additional images of storms which passed near South Florida during 1979 and 1980 were also used.

Some Discarded Assumptions

Although the assumptions appeared to be consistent with known patterns of hurricane behavior, most of them could not be applied to the present study. One assumption was that the shape of the area, where rainfall was influenced by a tropical cyclone, would be congruent with the shape of a

smaller area defined by specific values indicating heavy rainfall and strong wind. It was found, however, that the area of the South Florida Water Management District was too small to yield the patterns of data required to determine the shape of the intense part of the storm. A larger network of stations is needed.

Another assumption was that if a station which reported no rainfall on a given day lies between an area of known tropical cyclone influence and another station or stations which report some rainfall, it would be assumed the rain which fell at locations beyond the dry station is not the result of the tropical cyclone. This criterion assumes that any station which is under the influence of a tropical cyclone should receive at least a small quantity of rain during a 24-hour period. It was found, however, that relatively dry storms with poorly developed circulation, such as Tropical Storm "Amy" on June 26, 1975 (Figure 4), apparently pass some stations without dropping rain for 24-hour periods. Again, a denser network of weather stations spread across a larger area would be required to ascertain the rainband pattern for storms of the pre-imagery era.

A further difficulty in applying the second criterion is found in the quality of the raw data. Weather stations do not all record their data at the same time of day. Thus, rain which falls simultaneously in two different locations

may be attributed to different days and rain which falls on adjoining days may be attributed to the same day.

A third assumption was that for any location which is known to receive precipitation from a tropical storm or hurricane on at least one day, the period of time in which the place was influenced by the storm will be assumed to extend neither earlier than the last preceding dry day nor later than the next following day without rain. Widely spaced rainbands and erratic rainfall patterns impair the utility of this criterion as well, particularly for relatively dry storms.

The quality of the data (Appendices A and B) also presents another problem. Occasionally the passage of a hurricane may disable the rain gauge or prevent the observer from recording each day of rainfall. Several days of rainfall may go unrecorded or may be reported in a single observation. Published summaries of climatological data normally contain notes when cumulative quantities for several days are reported, but there appear to be unnoted instances of such reports as well, as for example at Okeechobee in 1939 when no rain was recorded for two days while the eye of a hurricane passed over the area, but over three inches was recorded for the following day when the storm center was several hundred miles away.

Procedures

Wide variability in the size, shape, intensity, and rainfall patterns of hurricanes and tropical storms precluded the prescription of any rigidly defined methodology for determining whether a given observation of rainfall was the result of a tropical cyclone system, at least within the confines of the area chosen for this study. A comprehensive study of the characteristics of the peripheral regions of tropical cyclones in the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico might provide some definitive statements on this topic, but such a study is beyond the scope of the present investigation.

The method used in this study was to plot each daily rainfall value on a map and to examine the spatial and temporal distributions of rainfall across the study area for the several days while each storm passed. Prior to the approach of a hurricane or tropical storm, the Water Management District usually had several days when rain was reported at few, if any, stations. If rain was found at a majority of stations, the quantities would tend to be small and randomly distributed across the area. With the approach of a tropical system, rainfall generally increased in frequency and quantity for several days before returning to pre-storm levels.

The principles of spatial and temporal continuity apply to tropical cyclone rainfall but not in the rigidly defined manner which was prescribed by earlier assumptions. If one

or several stations report no rain on a given day, those stations and others yet more distant from the storm center may still be judged to be under the influence of the tropical system if the proximity of the storm and the general pattern of circulation around it can be used to explain the pattern of rainfall observations.

In most instances, if rain was falling at a given location and there was a tropical weather system centered within 300 miles of the site, the rain was attributed to that storm. The 300-mile maximum radius conforms to the limit of the area for which Miller (1958) selected data. Miller, however, used that distance as a rigid arbitrary limit while the present findings suggest only that it is an approximate median of the radius of the area that would be influenced by a hurricane or tropical storm, which may extend from 150 to 600 miles from the storm center.

Analysis of Tropical Cyclone Rainfall

Summary and Discussion of Rainfall Data

The rainfall data which have been collected for nineteen weather stations in and near the South Florida Water Management District are divided into twelve five-year intervals and two thirty-year intervals as well as being summed for the full sixty-year period. These data concern annual rainfall and seasonal rainfall for the five-month

period of peak tropical cyclone activity for all nineteen stations (Table 4), annual and seasonal rainfall for each individual station (Tables 5 through 23 and Figures 5 and 6), tropical cyclone rainfall for each of the five months of the period of peak hurricane activity (Tables 24 through 28), and years and months of individual tropical cyclones (Table 29).

Mean annual rainfall from hurricanes for all stations for the sixty-year period is 2.05 inches, or 3.8 percent of the annual total rainfall and 5.8 percent of the seasonal rainfall. Mean rainfall from tropical storms is 1.74 inches, or 3.2 percent of the annual rainfall and 4.9 percent of the seasonal rainfall. Hurricanes and tropical storms combined comprise 3.79 inches of rain or 7.0 percent of the annual rainfall and 10.6 percent of the seasonal rainfall.

Mean annual rainfall from hurricanes for the individual stations ranges from 1.60 inches (3.0 percent) at Arcadia to 2.71 inches (4.4 percent) at Fort Lauderdale. Rainfall from tropical storms ranges from 1.19 inches (2.2 percent) at Bartow to 2.18 inches (4.1 percent) at Fort Myers. Rainfall from hurricanes and tropical storms combined ranges from 2.97 inches (5.7 percent) at Arcadia and 3.05 inches (5.6 percent) at Bartow to 4.66 inches (7.5 percent) at Fort Lauderdale and 4.30 inches (7.7 percent) at Fellsmere. Mean monthly rainfall from hurricanes and tropical storms combined ranges from 0.1 inch or 1.8 percent for July to 1.2

TABLE 4

TROPICAL CYCLONE RAINFALL--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	52.97	33.62	63.5	1.09	2.1	3.2	0.00	0.0	0.0	1.09	2.1	3.2
1924 - 28	5	56.26	37.43	66.5	3.54	6.3	9.5	2.65	4.7	7.1	6.19	11.0	16.5
1929 - 33	5	57.47	36.32	63.2	3.33	5.8	9.2	1.27	2.2	3.5	4.60	8.0	12.7
1934 - 38	5	53.40	34.41	64.4	1.52	2.8	4.4	3.04	5.7	8.8	4.56	8.5	13.3
1939 - 43	5	54.75	34.83	63.6	0.46	0.8	1.3	1.09	2.0	3.1	1.55	2.8	4.4
1944 - 48	5	57.42	40.57	70.7	7.22	12.6	17.8	1.74	3.0	4.3	8.96	15.6	22.1
1949 - 53	5	53.03	36.41	71.6	2.86	5.3	7.4	3.02	5.6	7.9	5.88	11.0	15.3
1954 - 58	5	53.19	32.04	60.2	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	56.40	37.17	65.8	1.72	3.0	4.6	2.60	4.6	7.0	4.31	7.6	11.6
1964 - 68	5	53.66	38.00	70.8	2.91	5.4	7.7	2.32	4.3	6.1	5.23	9.7	13.8
1969 - 73	5	51.23	33.68	63.3	0.00	0.0	0.0	1.16	2.2	3.4	1.16	2.2	3.4
1974 - 78	5	48.65	32.13	66.0	0.00	0.0	0.0	1.96	4.0	6.1	1.96	4.0	6.1
1919 - 48	30	55.38	36.20	65.4	2.36	5.2	7.9	1.63	2.9	4.5	4.45	8.1	12.4
1949 - 78	30	53.14	35.24	66.3	1.25	2.3	3.5	1.34	3.5	5.2	3.09	5.8	8.8
1919 - 78	60	54.26	35.72	65.8	2.05	3.8	5.8	1.74	3.2	4.9	3.79	7.0	10.6

TABLE 5

TROPICAL CYCLONE RAINFALL--ARCADIA

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	2	48.97	28.92	59.1	1.43	2.9	5.0	0.00	0.0	0.0	1.43	2.9	5.0
1924 - 28	5	54.54	39.75	72.9	2.04	3.7	5.1	1.81	3.3	4.5	3.84	7.0	9.7
1929 - 33	5	48.93	30.41	62.2	2.23	4.6	7.3	0.71	1.4	2.3	2.94	6.0	9.7
1934 - 38	5	50.52	34.47	68.2	1.62	3.2	4.7	2.34	4.6	6.8	3.96	7.6	11.5
1939 - 43	5	55.30	39.05	70.6	0.44	0.8	1.1	0.85	1.5	2.2	1.30	2.3	3.3
1944 - 48	5	55.95	39.62	70.8	4.68	8.4	11.8	1.14	2.0	2.9	5.83	10.4	14.7
1949 - 53	5	58.58	45.80	77.7	2.93	5.0	6.4	3.42	5.8	7.5	6.35	10.8	13.9
1954 - 58	5	50.02	28.15	56.3	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	56.45	35.79	63.4	1.63	2.9	4.5	0.52	0.9	1.5	2.15	3.8	6.0
1964 - 68	5	54.16	39.35	72.6	2.14	3.9	5.4	2.14	4.0	5.4	4.28	7.9	10.9
1969 - 73	5	46.94	31.93	65.2	0.00	0.0	0.0	1.38	2.8	4.3	1.38	2.8	4.3
1974 - 78	5	45.12	32.24	71.5	0.00	0.0	0.0	2.15	4.8	6.7	2.15	4.6	6.7
1919 - 48	27	52.75	35.83	67.9	2.07	3.9	5.8	1.14	2.2	3.2	3.22	6.1	9.0
1949 - 78	30	52.28	35.55	68.0	1.12	2.1	3.1	1.60	3.1	4.5	2.72	5.2	7.7
1919 - 78	57	52.50	35.68	68.0	1.60	3.0	4.5	1.37	2.6	3.8	2.97	5.7	8.3

TABLE 6

TROPICAL CYCLONE RAINFALL--AVON PARK

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	52.75	36.05	68.3	1.41	2.7	3.9	0.00	0.0	0.0	1.41	2.7	3.9
1924 - 28	5	52.16	38.01	72.9	2.64	5.1	7.0	2.00	3.8	5.3	4.65	8.9	12.2
1929 - 33	5	55.54	34.93	62.9	3.21	5.8	9.2	0.82	1.5	2.3	4.03	7.3	11.5
1934 - 38	5	50.94	32.14	63.1	0.82	1.6	2.5	2.18	4.3	6.8	3.00	5.9	9.3
1939 - 43	5	56.00	35.39	63.2	1.03	1.8	2.9	0.51	0.9	1.4	1.54	2.8	4.4
1944 - 48	5	59.54	43.67	73.3	6.69	11.2	15.3	1.12	1.9	2.6	7.80	13.1	17.9
1949 - 53	5	53.17	36.06	67.8	3.51	6.6	9.7	2.43	4.6	6.7	5.95	11.2	16.5
1954 - 58	5	52.26	33.14	63.4	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	58.89	37.13	63.0	2.04	3.5	5.5	2.15	3.6	5.8	4.19	7.1	11.3
1964 - 68	5	53.27	36.41	68.3	2.11	4.0	5.8	1.90	3.6	5.2	4.01	7.5	11.0
1969 - 73	5	51.70	34.06	65.9	0.00	0.0	0.0	1.11	2.1	3.3	1.11	2.1	3.3
1974 - 78	5	46.01	31.81	69.1	0.00	0.0	0.0	2.62	5.7	8.3	2.62	5.7	8.3
1919 - 48	30	54.49	36.86	67.6	2.63	4.8	7.1	1.11	2.0	3.0	3.74	6.9	10.1
1949 - 78	30	52.55	34.77	66.2	1.28	2.4	3.7	1.70	3.2	4.9	2.98	5.7	8.6
1919 - 78	60	53.52	35.79	66.9	1.96	3.7	5.5	1.40	2.6	3.9	3.36	6.3	9.4

TABLE 7

TROPICAL CYCLONE RAINFALL--BARTOW

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	5	53.98	33.45	62.0	1.42	2.6	4.2	0.00	0.0	0.0	1.42	2.6	4.2
1924 - 28	5	56.74	35.96	68.0	2.26	3.0	5.7	2.21	3.6	5.5	4.47	7.6	11.2
1929 - 33	5	60.10	37.45	62.3	3.36	5.6	9.0	0.83	1.4	2.2	4.19	7.0	11.2
1934 - 38	5	54.77	32.36	59.1	1.13	2.1	3.5	2.75	5.0	8.5	3.88	7.1	12.0
1939 - 43	5	53.22	32.42	60.9	0.50	0.9	1.5	0.54	1.0	1.7	1.04	2.0	3.2
1944 - 48	5	57.49	30.01	66.1	7.01	12.2	18.5	1.42	2.5	3.7	8.43	14.7	22.2
1949 - 53	5	53.72	36.75	68.4	2.88	5.4	7.8	1.13	2.1	3.1	4.00	7.5	10.9
1954 - 58	5	54.30	30.33	56.3	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	63.13	38.25	60.6	2.12	3.4	5.5	1.66	2.6	4.3	3.78	6.0	9.9
1964 - 68	5	48.03	30.94	64.4	1.67	3.5	5.4	1.34	2.8	4.3	3.01	6.3	9.7
1969 - 73	5	50.71	30.17	59.5	0.00	0.0	0.0	0.82	1.6	2.7	0.82	1.6	2.7
1974 - 78	5	46.96	29.48	60.7	0.00	0.0	0.0	1.55	3.2	5.3	1.55	3.2	5.3
1919 - 48	30	56.30	35.61	63.2	2.61	4.6	7.3	1.29	2.3	3.6	3.91	6.9	11.0
1949 - 78	30	53.17	32.75	61.6	1.11	2.1	3.4	1.08	2.0	3.3	2.19	4.1	6.7
1919 - 78	60	54.78	34.18	62.4	1.86	3.4	5.5	1.19	2.2	3.5	3.05	5.6	8.9

TABLE 8

TROPICAL CYCLONE RAINFALL--BELLE GLADE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	0	-----	-----	----	0.91	----	----	0.00	----	----	0.91	----	----
1924 - 28	3	59.27	38.84	65.5	4.03	6.8	10.4	2.21	3.7	5.7	6.24	10.5	16.1
1929 - 33	4	99.00	38.34	69.0	3.40	5.8	8.9	0.59	1.0	1.5	4.00	6.8	10.4
1934 - 38	5	55.01	37.03	67.3	1.32	2.4	3.6	2.90	5.3	7.8	4.21	7.7	11.4
1939 - 43	5	57.20	37.38	65.4	0.25	0.4	0.7	1.21	2.1	3.2	1.46	2.6	3.9
1944 - 48	5	64.87	45.44	70.0	8.45	13.0	18.6	2.86	4.4	6.3	11.31	17.4	24.9
1949 - 53	5	57.36	44.45	77.5	3.57	6.2	8.0	4.51	7.9	10.1	8.08	14.1	18.2
1954 - 58	5	55.76	33.56	60.2	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	56.87	38.97	67.9	1.84	3.1	4.6	2.33	4.0	5.8	4.17	7.1	10.4
1964 - 68	5	52.35	38.77	74.1	3.14	6.0	8.1	1.40	2.7	3.6	4.54	8.7	11.7
1969 - 73	5	61.00	36.56	63.2	0.00	0.0	0.0	0.51	0.8	1.3	0.51	0.8	1.3
1974 - 78	5	49.85	33.17	66.5	0.00	0.0	0.0	1.87	3.8	5.6	1.87	3.8	5.6
1919 - 48	22	59.06	39.43	66.8	3.06	5.2	7.8	1.63	2.8	4.1	4.69	7.9	11.9
1949 - 78	30	55.86	38.08	68.2	1.42	2.6	3.7	1.77	3.2	4.6	3.19	5.7	8.4
1919 - 78	52	57.21	38.68	67.6	2.24	3.9	5.6	1.70	3.0	4.4	3.94	6.9	10.2

TABLE 9

TROPICAL CYCLONE RAINFALL--EVERGLADES CITY

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	0	-----	-----	----	0.94	----	----	0.00	----	----	0.94	----	----
1924 - 28	2	47.13	40.05	85.0	3.46	7.3	9.7	3.94	8.4	9.8	7.40	15.7	18.5
1929 - 33	5	57.55	40.41	70.2	3.38	5.9	8.4	2.08	3.6	5.2	5.46	9.5	13.5
1934 - 38	5	55.67	40.86	73.4	3.34	6.0	8.2	5.24	9.4	12.8	8.58	15.4	21.0
1939 - 43	5	46.76	31.74	67.9	1.61	3.4	5.1	0.44	0.9	1.4	2.05	4.4	6.5
1944 - 48	5	58.32	42.97	73.7	7.01	12.0	16.3	2.58	4.4	6.0	9.59	16.4	22.3
1949 - 53	5	50.27	38.41	76.4	1.09	2.2	2.8	2.05	4.1	5.3	3.14	6.2	8.2
1954 - 58	5	56.07	35.59	63.5	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	56.53	42.24	74.7	2.13	3.8	5.0	2.97	5.2	7.0	5.09	9.0	12.1
1964 - 68	5	54.57	42.70	78.2	2.73	5.0	6.4	2.05	3.8	4.8	4.78	8.8	11.2
1969 - 73	5	52.99	39.31	74.2	0.00	0.0	0.0	1.15	2.2	2.9	1.15	2.2	2.9
1974 - 78	5	49.99	37.07	74.2	0.00	0.0	0.0	1.22	2.4	3.3	1.22	2.4	3.3
1919 - 48	22	53.90	39.09	72.5	3.29	6.1	8.4	2.36	4.4	6.1	5.67	10.5	14.5
1949 - 78	30	53.40	39.22	73.4	0.99	1.9	2.5	1.57	2.9	4.0	2.56	4.8	6.5
1919 - 78	52	53.61	39.16	73.1	2.14	4.0	5.5	1.90	3.7	5.0	4.12	7.7	10.5

TABLE 10

TROPICAL CYCLONE RAINFALL--FELLSMERE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	48.06	34.25	71.3	0.59	1.2	1.7	0.00	0.0	0.0	0.59	1.2	1.7
1924 - 28	5	61.87	41.62	67.3	4.91	7.9	11.8	3.24	5.2	7.8	8.14	13.2	19.6
1929 - 33	5	62.06	38.45	62.0	2.75	4.4	7.2	1.42	2.3	3.7	4.17	6.7	10.8
1934 - 38	5	59.49	38.43	64.6	0.93	1.6	2.4	2.95	5.0	7.7	3.88	6.5	10.1
1939 - 43	5	63.00	41.45	64.9	0.42	0.7	1.0	1.86	2.9	4.5	2.29	3.6	5.5
1944 - 48	5	60.20	45.48	75.6	8.22	13.6	18.1	2.57	4.3	5.7	10.79	17.9	23.7
1949 - 53	4	58.25	39.05	67.0	3.98	6.8	10.2	4.24	7.3	10.9	8.23	14.1	21.1
1954 - 58	5	54.96	35.53	64.7	0.00	0.0	0.0	0.30	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	55.48	35.61	64.2	1.13	2.0	3.2	5.03	9.1	14.1	6.16	11.1	17.3
1964 - 68	4	45.14	33.24	73.6	2.55	5.7	7.7	2.20	4.9	6.6	4.76	10.5	14.3
1969 - 73	3	46.68	30.74	65.9	0.00	0.0	0.0	1.27	2.7	4.1	1.27	2.7	4.1
1974 - 78	3	46.03	29.41	63.9	0.00	0.0	0.0	1.37	3.0	4.7	1.37	3.0	4.7
1919 - 48	30	59.26	39.95	67.4	2.97	5.0	7.4	2.01	3.4	5.0	4.98	8.4	12.5
1949 - 78	24	51.83	34.25	66.1	1.28	2.5	3.7	2.35	4.5	6.9	3.63	7.0	10.6
1919 - 78	54	55.96	37.25	66.6	2.12	3.8	5.7	2.18	3.9	5.9	4.30	7.7	11.6

TABLE 11

TROPICAL CYCLONE RAINFALL--FORT LAUDERDALE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	62.49	37.20	59.5	1.22	2.0	3.3	0.00	0.0	0.0	1.22	2.0	3.3
1924 - 28	4	66.14	40.79	61.7	7.51	11.4	18.4	3.83	5.8	9.4	11.34	17.1	27.8
1929 - 33	5	70.62	45.45	64.4	3.73	5.3	8.2	1.21	1.7	2.7	4.95	7.0	10.9
1934 - 38	4	58.78	36.33	61.8	1.33	2.3	3.7	2.82	4.8	7.8	4.15	7.1	11.4
1939 - 43	5	54.97	30.94	56.3	0.15	0.3	0.5	1.24	2.3	4.0	1.39	2.5	4.5
1944 - 48	3	71.61	45.70	63.8	9.50	13.3	20.8	1.99	2.8	4.3	11.48	16.0	25.1
1949 - 53	5	54.69	37.54	68.6	1.96	3.6	5.2	3.57	6.5	9.5	5.53	10.1	14.7
1954 - 58	5	62.61	33.33	53.2	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	57.38	38.33	66.8	1.74	3.0	4.5	2.91	5.1	7.6	4.65	8.1	12.1
1964 - 68	5	67.92	48.13	70.9	5.37	7.9	11.2	2.21	3.3	4.6	7.58	11.2	15.8
1969 - 73	5	59.73	33.95	56.3	0.00	0.0	0.0	1.06	1.8	3.1	1.06	1.8	3.1
1974 - 78	5	58.76	36.23	61.7	0.00	0.0	0.0	2.62	4.5	7.2	2.62	4.5	7.2
1919 - 48	26	63.65	39.13	61.5	3.91	6.1	10.0	1.85	2.9	4.7	5.75	9.0	14.7
1949 - 78	30	60.19	37.92	63.0	1.51	2.5	4.0	2.06	3.4	5.4	3.57	5.9	9.4
1919 - 78	56	61.79	38.50	62.3	2.71	4.4	7.0	1.95	3.2	5.1	4.66	7.5	12.1

TABLE 12

TROPICAL CYCLONE RAINFALL--FORT MYERS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	54.76	40.07	73.2	0.98	1.8	2.4	0.00	0.0	0.0	0.98	1.8	2.4
1924 - 28	5	52.07	39.11	75.1	3.89	7.5	9.9	3.39	6.5	8.7	7.28	14.0	18.6
1929 - 33	5	52.50	34.33	65.4	2.04	3.9	5.0	2.79	5.3	8.1	4.83	9.2	14.1
1934 - 38	5	50.01	36.59	73.2	2.48	5.0	6.8	3.35	6.7	9.2	5.83	11.7	15.9
1939 - 43	5	52.65	41.19	78.2	0.09	0.2	0.2	0.95	1.6	2.3	1.04	1.8	2.5
1944 - 48	5	51.47	30.43	74.7	7.44	14.5	19.4	1.49	2.9	3.9	6.93	17.4	22.2
1949 - 53	5	52.40	42.35	80.8	1.30	2.5	3.1	3.92	7.5	9.3	5.22	10.0	12.3
1954 - 58	5	52.77	34.04	64.5	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	55.36	39.54	71.4	2.53	4.6	6.4	3.34	6.0	8.5	5.88	10.6	14.9
1964 - 68	5	45.67	37.10	74.7	1.88	3.8	5.1	2.34	4.7	6.3	4.21	8.5	11.4
1969 - 73	5	55.83	37.77	67.7	0.00	0.0	0.0	2.13	3.8	5.6	2.13	3.8	5.6
1974 - 78	5	52.03	40.25	77.4	0.00	0.0	0.0	2.48	4.8	6.2	2.48	4.8	6.2
1919 - 48	30	53.24	38.28	71.9	2.82	5.3	7.4	2.00	3.7	5.2	4.82	9.0	12.6
1949 - 78	30	53.01	38.51	72.6	0.95	1.8	2.5	2.37	4.5	6.2	3.32	6.3	8.6
1919 - 78	60	53.13	38.40	72.3	1.89	3.5	4.9	2.13	4.1	5.7	4.07	7.7	10.6

TABLE 13

TROPICAL CYCLONE RAINFALL--FORT PIERCE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	5	47.28	26.22	55.5	0.98	2.1	3.7	0.00	0.0	0.0	0.98	2.1	3.7
1924 - 28	5	52.60	33.79	64.2	4.06	9.2	14.4	3.24	6.2	9.6	8.10	15.4	24.0
1929 - 33	5	56.99	32.59	57.2	2.65	5.0	8.8	0.90	1.6	2.8	3.75	6.6	11.5
1934 - 38	5	53.80	31.15	57.9	0.48	0.9	1.5	1.01	3.4	5.8	2.29	4.3	7.4
1939 - 43	5	52.54	30.34	57.8	0.29	0.6	1.0	2.12	4.0	7.0	2.42	4.6	8.0
1944 - 48	5	55.91	36.66	66.0	7.09	12.7	19.2	3.57	6.4	9.7	10.66	19.1	28.9
1949 - 53	5	54.54	35.24	64.6	3.18	6.2	9.6	3.06	5.6	8.7	6.44	11.8	18.3
1954 - 58	5	51.11	32.46	63.5	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	56.30	36.02	65.4	1.54	2.7	4.2	3.81	6.8	10.3	5.35	9.5	14.5
1964 - 68	5	49.05	32.85	67.0	3.22	6.6	9.8	2.35	4.8	7.1	5.56	11.3	16.9
1969 - 73	5	55.85	33.26	59.6	0.00	0.0	0.0	0.88	1.6	2.6	0.86	1.6	2.6
1974 - 78	5	47.88	28.04	58.6	0.00	0.0	0.0	1.24	2.6	4.4	1.24	2.6	4.4
1919 - 48	30	53.19	31.83	59.9	2.76	5.2	8.7	1.94	3.6	6.1	4.70	8.8	14.8
1949 - 78	30	52.46	33.11	63.1	1.36	2.6	4.1	1.89	3.6	5.7	3.25	6.2	9.8
1919 - 78	60	52.82	32.47	61.5	2.06	3.9	6.3	1.92	3.6	5.9	3.97	7.5	12.2

TABLE 14

TROPICAL CYCLONE RAINFALL--HOMESTEAD

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	4	58.64	37.05	63.2	0.98	1.7	2.7	0.00	0.0	0.0	0.98	1.7	2.7
1924 - 28	1	64.92	40.73	62.7	2.56	3.9	6.3	4.10	6.3	10.1	6.66	10.3	16.4
1929 - 33	3	64.88	41.91	64.6	3.92	6.0	9.4	1.34	2.1	3.2	5.26	8.1	12.5
1934 - 38	5	64.97	45.02	69.3	3.96	6.1	8.8	2.62	4.0	5.8	6.53	10.1	14.6
1939 - 43	5	66.20	47.65	72.0	0.17	0.3	0.4	1.59	2.4	3.3	1.76	2.7	3.7
1944 - 48	5	66.87	50.66	75.8	8.18	12.2	16.1	1.98	3.0	3.9	10.15	15.2	20.0
1949 - 53	5	57.83	42.27	73.1	1.38	2.4	3.3	2.19	3.8	5.2	3.56	6.2	8.4
1954 - 58	5	60.39	36.82	61.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	66.63	46.03	69.1	1.97	3.0	4.3	2.37	3.6	5.1	4.33	6.5	9.4
1964 - 68	5	61.04	45.68	74.8	4.76	7.8	10.4	2.70	4.4	5.8	7.46	12.2	16.3
1969 - 73	5	57.63	40.82	70.8	0.00	0.0	0.0	1.02	1.8	2.5	1.02	1.8	2.5
1974 - 78	5	58.93	39.51	67.1	0.00	0.0	0.0	1.71	2.9	4.3	1.71	2.9	4.3
1919 - 48	23	64.53	44.67	69.2	3.29	5.1	7.4	1.94	3.0	4.3	5.23	8.1	11.7
1949 - 78	30	60.41	41.86	69.3	1.35	2.2	3.2	1.66	2.8	4.0	3.01	5.0	7.2
1919 - 78	53	62.20	43.11	69.3	2.32	3.7	5.4	1.80	2.9	4.2	4.12	6.6	9.6

TABLE 15

TROPICAL CYCLONE RAINFALL--ISLEWORTH

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	4	47.09	28.85	61.3	0.94	2.0	3.2	0.00	0.0	0.0	0.94	2.0	3.2
1924 - 28	4	49.48	30.62	61.9	3.11	6.3	10.2	0.92	1.9	3.0	4.03	8.2	13.2
1929 - 33	5	52.53	33.04	62.9	2.21	4.2	6.7	0.33	0.6	1.0	2.53	4.8	7.7
1934 - 38	5	53.36	33.05	61.9	0.50	0.9	1.5	3.37	6.3	10.2	3.87	7.2	11.7
1939 - 43	2	50.48	34.73	68.8	0.28	0.5	0.8	0.88	1.8	2.5	1.16	2.3	3.3
1944 - 48	5	58.03	41.14	70.9	6.93	11.9	16.9	1.21	2.1	2.9	8.14	14.0	19.8
1949 - 53	5	51.67	33.78	65.4	4.45	8.6	13.2	1.17	2.3	3.5	5.62	10.9	16.6
1954 - 58	5	47.83	26.03	54.1	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	57.62	34.28	59.5	1.54	2.7	4.5	1.35	2.3	3.9	2.89	5.0	8.4
1964 - 68	5	49.99	33.06	66.1	3.25	6.5	9.8	2.41	4.8	7.3	5.67	11.3	17.1
1969 - 73	5	51.39	29.26	56.9	0.00	0.0	0.0	1.12	2.2	3.8	1.12	2.2	3.8
1974 - 78	5	47.71	30.61	64.2	0.00	0.0	0.0	2.24	4.7	7.3	2.24	4.7	7.3
1919 - 48	25	52.28	33.66	64.4	2.33	4.5	6.9	1.12	2.1	3.3	3.45	6.6	10.2
1949 - 78	30	51.04	31.31	61.3	1.54	3.0	4.9	1.38	2.7	4.4	2.92	5.7	9.3
1919 - 78	55	51.60	32.42	62.8	1.93	3.7	6.0	1.25	2.4	3.9	3.18	6.2	9.8

TABLE 16

TROPICAL CYCLONE RAINFALL--KISSIMMEE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	2	56.60	33.23	58.7	1.35	2.4	4.1	0.00	0.0	0.0	1.35	2.4	4.1
1924 - 28	0	-----	33.76	----	2.10	----	6.2	1.40	----	4.1	3.49	----	10.3
1929 - 33	4	51.57	28.32	56.1	2.79	5.4	9.6	0.23	0.4	0.8	3.02	5.9	10.4
1934 - 38	5	47.46	27.60	58.2	0.74	1.6	2.7	3.03	6.4	11.0	3.77	7.9	13.7
1939 - 43	5	50.91	32.55	63.9	0.33	0.6	1.0	1.24	2.4	3.8	1.56	3.1	4.8
1944 - 48	5	51.59	34.19	66.3	8.30	16.1	24.3	0.71	1.4	2.1	9.01	17.5	26.3
1949 - 53	5	53.51	34.96	65.3	4.15	7.8	11.9	1.71	3.2	4.9	5.86	11.0	16.8
1954 - 58	5	48.72	30.54	62.7	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	56.44	35.58	63.0	1.62	2.9	4.6	2.32	4.1	6.5	3.94	7.0	11.1
1964 - 68	5	46.65	31.25	67.0	2.29	4.9	7.3	2.71	5.8	8.7	5.00	10.7	16.0
1969 - 73	5	46.31	28.12	60.7	0.00	0.0	0.0	0.83	1.8	2.9	0.83	1.8	2.9
1974 - 78	5	43.74	29.47	67.4	0.00	0.0	0.0	1.93	4.4	6.5	1.93	4.4	6.5
1919 - 48	21	50.92	31.26	61.4	2.60	5.1	8.3	1.10	2.2	3.5	3.70	7.3	11.8
1949 - 78	30	49.23	31.65	64.3	1.34	2.7	4.2	1.58	3.2	5.0	2.93	5.9	9.2
1919 - 78	51	49.92	31.49	63.1	1.97	4.0	6.3	1.34	2.7	4.3	3.31	6.6	10.5

TABLE 17

TROPICAL CYCLONE RAINFALL--LA BELLE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	0	-----	-----	----	0.75	----	----	0.00	----	----	0.75	----	----
1924 - 28	0	-----	-----	----	3.62	----	----	2.49	----	----	6.10	----	----
1929 - 33	2	48.56	30.73	63.3	3.06	6.3	10.0	2.31	4.8	7.5	5.37	11.1	17.5
1934 - 38	5	45.45	31.73	69.8	1.61	3.5	5.1	4.53	10.0	14.3	6.14	13.5	19.4
1939 - 43	5	48.22	29.73	61.7	0.20	0.4	0.7	0.55	1.1	1.9	0.75	1.6	2.5
1944 - 48	5	59.21	45.34	76.6	7.14	12.1	15.7	1.51	2.6	3.3	8.65	14.6	19.1
1949 - 53	5	53.64	41.30	77.9	1.33	2.5	3.2	4.12	7.7	9.8	5.44	10.1	13.0
1954 - 58	5	54.05	31.99	59.2	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	52.63	34.95	66.4	1.70	3.2	4.9	1.97	3.3	5.6	3.68	7.0	10.5
1964 - 68	5	55.80	41.00	73.6	1.77	3.2	4.3	1.70	3.0	4.1	3.47	6.2	8.4
1969 - 73	5	49.67	30.91	62.2	0.00	0.0	0.0	0.69	1.4	2.2	0.69	1.4	2.2
1974 - 78	5	44.67	30.75	68.8	0.00	0.0	0.0	2.47	5.5	8.0	2.47	5.5	8.0
1919 - 48	17	50.68	35.03	69.1	2.73	5.4	7.8	1.90	3.7	5.4	4.63	9.1	13.2
1949 - 78	30	51.74	35.25	68.1	0.50	1.5	2.3	1.82	3.5	5.2	2.62	5.1	7.4
1919 - 78	47	51.36	35.17	68.5	1.77	3.4	5.0	1.86	3.6	5.3	3.63	7.1	10.3

TABLE 18

TROPICAL CYCLONE RAINFALL--MIAMI

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	% ANN	HURRICANE RAIN MEAN	% ANN	% SEA	TROP. STORM RAIN MEAN	% ANN	% SEA	HURR + TROP. ST. MEAN	% ANN	% SEA
1919 - 23	5	52.29	30.66	58.6	0.35	0.7	1.1	0.00	0.0	0.0	0.35	0.7	1.1
1924 - 28	5	58.23	36.22	62.2	3.84	6.6	10.6	3.38	6.7	10.7	7.72	13.3	21.3
1929 - 33	5	72.94	47.01	64.5	4.72	6.5	10.0	2.41	3.3	5.1	7.13	9.8	15.2
1934 - 38	5	59.05	37.96	64.3	1.39	3.4	5.2	3.11	5.3	8.2	5.10	8.6	13.4
1939 - 43	5	56.40	33.40	59.2	0.11	0.2	0.3	0.32	0.6	1.0	0.43	0.8	1.3
1944 - 48	5	45.69	30.10	65.9	4.45	9.7	14.8	1.46	3.2	4.9	5.91	12.9	19.6
1949 - 53	5	52.37	37.42	70.8	1.77	3.4	4.7	3.05	5.8	8.1	4.82	9.1	12.9
1954 - 58	5	56.66	32.93	58.1	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	57.93	38.49	66.4	2.31	4.0	6.0	3.99	6.9	10.4	6.30	10.9	16.4
1964 - 68	5	70.05	50.17	71.6	5.96	8.5	11.9	3.10	4.4	6.2	9.06	12.9	18.1
1969 - 73	5	56.66	36.62	64.6	0.00	0.0	0.0	2.08	3.7	5.7	2.08	3.7	5.7
1974 - 78	5	50.96	30.11	59.1	0.00	0.0	0.0	1.36	2.7	4.5	1.36	2.7	4.5
1919 - 48	30	57.43	35.89	62.5	2.58	4.5	7.2	1.86	3.2	5.2	4.44	7.7	12.4
1949 - 78	30	57.52	37.62	65.4	1.67	2.9	4.4	2.26	3.9	6.0	3.94	6.8	10.5
1919 - 78	60	57.48	36.76	64.0	2.13	3.7	5.8	2.06	3.6	5.6	4.19	7.3	11.4

TABLE 19

TROPICAL CYCLONE RAINFALL--MOORE HAVEN

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	4	52.67	35.31	68.0	0.64	1.2	1.8	0.00	0.0	0.0	0.64	1.2	1.8
1924 - 28	4	51.03	37.44	73.4	2.75	5.4	7.3	1.99	3.9	5.3	4.73	9.3	12.6
1929 - 33	5	51.46	34.09	66.2	2.19	4.2	6.4	1.59	3.1	4.7	3.78	7.3	11.1
1934 - 38	5	48.10	30.94	64.3	1.04	2.2	3.4	2.61	5.4	8.4	3.65	7.6	11.8
1939 - 43	5	50.93	32.61	64.1	0.40	0.8	1.2	1.00	2.0	3.1	1.39	2.7	4.3
1944 - 48	5	50.11	36.45	72.7	6.59	13.2	18.1	1.39	3.8	5.2	8.46	16.9	23.3
1949 - 53	5	51.33	37.92	73.9	2.15	4.2	5.7	3.81	7.4	10.1	5.97	11.6	15.7
1954 - 58	5	49.96	30.18	60.4	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	50.83	32.83	64.6	2.04	4.0	6.2	1.85	3.6	5.6	3.89	7.7	11.9
1964 - 68	5	46.12	32.83	71.2	2.11	4.6	6.4	1.67	3.6	5.1	3.78	8.2	11.5
1969 - 73	5	50.80	34.42	67.8	0.00	0.0	0.0	1.23	2.4	3.6	1.23	2.4	3.6
1974 - 78	5	47.75	32.14	67.3	0.00	0.0	0.0	1.94	4.1	6.0	1.94	4.1	6.0
1919 - 48	28	50.62	34.41	68.0	2.27	4.5	6.6	1.51	3.0	4.4	3.78	7.5	11.0
1949 - 78	30	49.47	33.39	67.5	1.05	2.1	3.1	1.75	3.5	5.2	2.80	5.7	8.4
1919 - 78	58	50.02	33.88	67.7	1.66	3.3	4.9	1.63	3.3	4.8	3.29	6.6	9.7

TABLE 20

TROPICAL CYCLONE RAINFALL--OKEECHOBEE

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	1	46.25	26.72	57.8	0.40	0.9	1.5	0.00	0.0	0.0	0.40	0.9	1.5
1924 - 28	0	-----	31.36	----	4.11	----	13.1	1.19	----	3.8	5.31	----	16.9
1929 - 33	4	49.19	33.71	66.5	4.10	8.3	12.2	1.44	2.9	4.3	5.54	11.3	16.4
1934 - 38	5	50.37	31.50	62.9	0.97	1.9	3.1	2.99	6.0	9.5	3.96	7.9	12.6
1939 - 43	5	45.09	26.51	58.1	0.74	1.5	2.6	1.31	2.7	4.6	2.05	4.2	7.2
1944 - 48	5	48.09	28.93	60.2	5.73	11.9	17.8	0.90	1.9	3.1	6.63	13.8	22.9
1949 - 53	5	46.58	33.13	71.1	2.92	6.3	8.8	4.09	8.8	12.3	7.01	15.1	21.2
1954 - 58	5	49.96	30.45	61.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	46.21	31.04	67.2	0.61	1.3	2.0	3.03	6.6	9.8	3.64	7.9	11.7
1964 - 68	5	44.57	32.21	72.3	2.73	6.1	8.5	1.52	3.4	4.7	4.26	9.6	13.2
1969 - 73	5	48.95	30.37	62.0	0.00	0.0	0.0	1.13	2.3	3.7	1.13	2.3	3.7
1974 - 78	4	35.26	21.54	61.1	0.00	0.0	0.0	1.28	3.6	5.9	1.28	3.6	5.9
1919 - 48	20	48.96	30.29	61.9	2.68	5.5	8.8	1.31	2.7	4.3	3.98	8.1	13.1
1949 - 78	29	45.60	30.07	66.0	1.04	2.3	3.5	1.84	4.0	6.1	2.89	6.3	9.6
1919 - 78	49	46.97	30.10	64.2	1.86	4.0	6.2	1.57	3.4	5.2	3.43	7.3	11.4

TABLE 21

TROPICAL CYCLONE RAINFALL--ORLANDO

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	53.56	32.65	61.0	2.29	4.3	7.0	0.00	0.0	0.0	2.29	4.3	7.0
1924 - 28	5	52.55	33.39	63.4	2.10	4.0	6.3	2.38	4.5	7.1	4.48	8.5	13.4
1929 - 33	5	51.64	31.35	60.7	2.79	5.4	8.9	0.12	0.2	0.4	2.92	5.7	9.3
1934 - 38	5	49.14	30.49	62.0	0.41	0.8	1.3	3.57	7.3	11.7	3.98	8.1	13.1
1939 - 43	5	51.36	32.56	63.4	0.27	0.5	0.8	1.27	2.5	3.9	1.54	3.0	4.7
1944 - 48	5	55.30	39.06	72.5	8.39	15.3	21.0	0.98	1.8	2.5	9.37	17.0	23.5
1949 - 53	5	53.10	34.58	65.1	5.24	9.9	15.1	1.74	3.3	5.0	6.98	13.1	20.2
1954 - 58	5	47.65	30.99	65.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	53.90	34.48	63.9	0.81	1.5	2.3	1.69	3.1	4.9	2.50	4.6	7.2
1964 - 68	5	50.04	32.42	64.8	2.63	5.3	8.1	3.74	7.5	11.5	6.38	12.7	19.7
1969 - 73	5	49.19	29.14	59.2	0.00	0.0	0.0	0.81	1.6	2.8	0.81	1.6	2.8
1974 - 78	5	45.43	30.12	66.3	0.00	0.0	0.0	2.33	5.1	7.7	2.33	5.1	7.7
1919 - 48	30	52.22	33.38	63.9	2.71	5.2	8.1	1.39	2.7	4.2	4.10	7.8	12.3
1949 - 78	30	49.90	31.96	64.3	1.45	2.9	4.5	1.72	3.4	5.4	3.17	6.3	9.9
1919 - 78	60	51.06	32.67	64.0	2.08	4.1	6.4	1.55	3.0	4.8	3.63	7.1	11.1

TABLE 22

TROPICAL CYCLONE RAINFALL--PUNTA GORDA

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	3	52.58	36.72	69.8	1.21	2.3	3.3	0.00	0.0	0.0	1.21	2.3	3.3
1924 - 28	4	53.55	37.98	70.9	0.60	1.3	1.8	3.76	7.0	9.9	4.44	8.3	11.7
1929 - 33	5	50.41	32.92	65.3	2.15	4.3	6.5	1.46	2.9	4.4	3.60	7.1	10.9
1934 - 38	5	50.15	34.17	68.1	3.11	6.2	9.1	2.53	5.0	7.4	5.64	11.2	16.5
1939 - 43	5	51.48	34.23	66.5	0.35	0.7	1.0	1.26	2.5	3.7	1.61	3.1	4.7
1944 - 48	5	57.66	42.14	73.1	6.11	10.6	14.5	1.05	1.8	2.5	7.17	12.4	17.0
1949 - 53	5	49.56	36.68	74.1	2.75	5.5	7.1	4.03	8.1	10.4	6.78	13.7	17.5
1954 - 58	5	49.40	31.27	63.3	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	57.37	38.36	66.9	2.36	4.1	6.2	2.41	4.2	6.3	4.77	8.3	12.4
1964 - 68	4	45.75	33.71	73.7	1.46	3.2	4.3	2.12	4.6	6.3	3.58	7.8	10.6
1969 - 73	5	49.31	31.40	63.7	0.00	0.0	0.0	0.97	2.0	3.1	0.97	2.0	3.1
1974 - 78	5	45.37	32.63	71.9	0.00	0.0	0.0	2.64	5.8	8.1	2.64	5.8	8.1
1919 - 48	27	52.61	36.33	69.1	2.27	4.3	6.2	1.68	3.2	4.6	3.95	7.5	10.9
1949 - 78	29	49.59	34.36	69.3	1.09	2.2	3.2	2.03	4.1	5.9	3.12	6.3	9.1
1919 - 78	56	51.05	35.33	69.2	1.68	3.3	4.8	1.85	3.6	5.2	3.53	6.9	10.0

TABLE 23

TROPICAL CYCLONE RAINFALL--WEST PALM BEACH

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	HURR. SEASON (JUNE - OCT) MEAN	HURR. SEASON (JUNE - OCT) % ANN	HURRICANE RAIN MEAN	HURRICANE RAIN % ANN	HURRICANE RAIN % SEA	TROP. STORM RAIN MEAN	TROP. STORM RAIN % ANN	TROP. STORM RAIN % SEA	HURR + TROP. ST. MEAN	HURR + TROP. ST. % ANN	HURR + TROP. ST. % SEA
1919 - 23	5	56.87	34.81	61.2	1.18	2.1	3.4	0.00	0.0	0.0	1.18	2.1	3.4
1924 - 28	2	67.83	33.89	50.0	5.33	7.9	15.7	1.76	2.6	5.2	7.09	10.5	20.9
1929 - 33	5	66.55	40.53	60.9	7.72	11.6	19.0	1.49	2.2	3.7	9.21	13.8	22.7
1934 - 38	5	58.33	32.13	55.1	0.70	1.2	2.2	3.04	5.2	9.4	3.74	6.4	11.6
1939 - 43	5	64.00	37.05	57.2	0.51	0.8	1.4	1.07	1.7	2.9	1.58	2.4	4.3
1944 - 48	5	70.98	47.59	67.0	8.66	12.2	18.2	2.51	3.5	5.3	11.17	15.7	23.5
1949 - 53	5	56.31	39.56	70.3	3.27	5.8	8.3	3.16	5.6	8.0	6.43	11.4	16.2
1954 - 58	5	55.41	29.92	54.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959 - 63	5	55.01	36.58	66.5	0.94	1.7	2.6	3.61	6.6	9.9	4.55	8.3	12.4
1964 - 68	5	69.25	46.66	70.3	3.51	5.1	7.2	3.17	4.6	6.5	6.68	9.6	13.7
1969 - 73	5	63.25	36.92	58.4	0.00	0.0	0.0	1.04	1.6	2.8	1.04	1.6	2.8
1974 - 78	5	56.93	31.10	54.6	0.00	0.0	0.0	1.86	3.3	6.0	1.86	3.3	6.0
1919 - 48	27	63.83	37.80	59.2	4.02	6.3	10.6	1.65	2.6	4.4	5.66	8.9	15.0
1949 - 78	30	59.36	37.12	62.5	1.29	2.2	3.5	2.14	3.6	5.8	3.43	5.8	9.2
1919 - 78	57	61.48	37.45	60.9	2.65	4.3	7.1	1.89	3.1	5.1	4.54	7.4	12.1

TABLE 24

JUNE RAINFALL--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	TOTAL MEAN	TOTAL % ANN	HURRICANE MEAN	HURRICANE % MO	TROP STORM MEAN	TROP STORM % MO	HURR & TS MEAN	HURR & TS % MO
1919 - 23	5	52.97	6.8	12.9	0.0	0.0	0.0	0.0	0.0	0.0
1924 - 28	5	56.26	7.0	12.4	0.0	0.0	0.0	0.0	0.0	0.0
1929 - 33	5	57.47	8.2	14.3	0.0	0.0	0.0	0.0	0.0	0.0
1934 - 38	5	53.40	9.0	16.9	0.0	0.0	1.2	12.9	1.2	12.9
1939 - 43	5	54.75	9.0	16.5	0.0	0.0	0.0	0.0	0.0	0.0
1944 - 48	5	57.42	8.1	14.1	1.3	16.1	0.0	0.0	1.3	16.1
1949 - 53	5	53.63	6.6	12.3	0.0	0.0	0.0	0.0	0.0	0.0
1954 - 58	5	53.19	7.0	13.1	0.0	0.0	0.0	0.0	0.0	0.0
1959 - 63	5	56.48	9.1	16.2	0.0	0.0	1.6	17.2	1.6	17.2
1964 - 68	5	53.66	10.8	20.2	0.8	6.9	2.1	19.0	2.8	25.9
1969 - 73	5	53.23	8.1	15.3	0.0	0.0	0.0	0.0	0.0	0.0
1974 - 78	5	48.65	8.2	16.9	0.0	0.0	1.3	16.4	1.3	16.4
1919 - 48	30	55.38	8.0	14.5	0.2	2.7	0.2	2.4	0.4	5.1
1949 - 78	30	53.14	8.3	15.6	0.1	1.5	0.8	10.0	1.0	11.5
1919 - 78	60	54.26	8.2	15.1	0.2	2.1	0.5	6.3	0.7	8.4

TABLE 25

JULY RAINFALL--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	TOTAL MEAN	TOTAL % ANN	HURRICANE MEAN	HURRICANE % MO	TROP STORM MEAN	TROP STORM % MO	HURR & TS MEAN	HURR & TS % MO
1919 - 23	5	52.97	7.6	14.3	0.0	0.0	0.0	0.0	0.0	0.0
1924 - 28	5	56.26	8.4	14.9	0.4	4.3	0.0	0.0	0.4	4.3
1929 - 33	5	57.47	6.4	11.1	0.6	9.1	0.0	0.0	0.6	9.1
1934 - 38	5	53.40	7.1	13.4	0.2	3.0	0.4	6.0	0.6	9.0
1939 - 43	5	54.75	7.8	14.3	0.0	0.0	0.0	0.0	0.0	0.0
1944 - 48	5	57.42	9.0	15.7	0.0	0.0	0.0	0.0	0.0	0.0
1949 - 53	5	53.63	7.5	14.0	0.0	0.0	0.0	0.0	0.0	0.0
1954 - 58	5	53.19	6.9	13.0	0.0	0.0	0.0	0.0	0.0	0.0
1959 - 63	5	56.48	6.9	12.1	0.0	0.0	0.0	0.0	0.0	0.0
1964 - 68	5	53.66	7.5	14.0	0.0	0.0	0.0	0.0	0.0	0.0
1969 - 73	5	53.23	7.0	13.2	0.0	0.0	0.0	0.0	0.0	0.0
1974 - 78	5	48.65	8.0	16.4	0.0	0.0	0.0	0.0	0.0	0.0
1919 - 48	30	55.38	7.7	13.9	0.2	2.5	0.1	0.9	0.3	3.4
1949 - 78	30	53.14	7.3	13.8	0.0	0.0	0.0	0.0	0.0	0.0
1919 - 78	60	54.26	7.5	13.9	0.1	1.3	0.0	0.5	0.1	1.8

TABLE 26

AUGUST RAINFALL--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	TOTAL MEAN	TOTAL % ANN	HURRICANE MEAN	HURRICANE % MO	TROP STORM MEAN	TROP STORM % MO	HURR & TS MEAN	HURR & TS % MO
1919 - 23	5	52.97	6.1	11.6	0.0	0.0	0.0	0.0	0.0	0.0
1924 - 28	5	56.26	8.6	15.3	0.9	10.9	0.6	7.3	1.6	18.2
1929 - 33	5	57.47	7.3	12.6	0.1	1.9	0.7	10.3	0.9	12.2
1934 - 38	5	53.40	5.8	10.8	0.0	0.0	0.5	8.4	0.5	8.4
1939 - 43	5	54.75	7.0	12.7	0.4	5.0	0.3	3.9	0.6	8.9
1944 - 48	5	57.42	7.3	12.6	0.0	0.0	0.2	3.0	0.2	3.0
1949 - 53	5	53.63	8.5	15.9	0.9	10.6	0.7	8.6	1.6	19.3
1954 - 58	5	53.19	6.4	12.1	0.0	0.0	0.0	0.0	0.0	0.0
1959 - 63	5	56.48	6.9	12.2	0.0	0.0	0.2	2.7	0.2	2.7
1964 - 68	5	53.66	7.2	13.3	0.5	6.4	0.2	2.6	0.6	9.0
1969 - 73	5	53.23	7.5	14.1	0.0	0.0	0.2	2.5	0.2	2.5
1974 - 78	5	48.65	6.5	13.3	0.0	0.0	0.5	7.2	0.5	7.2
1919 - 48	30	55.38	7.0	12.6	0.2	3.4	0.4	5.6	0.6	9.0
1949 - 78	30	53.14	7.2	13.5	0.2	3.2	0.3	4.1	0.5	7.3
1919 - 78	60	54.26	7.1	13.1	0.2	3.3	0.3	4.8	0.6	8.1

TABLE 27

SEPTEMBER RAINFALL--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	TOTAL MEAN	TOTAL % ANN	HURRICANE MEAN	HURRICANE % MO	TROP STORM MEAN	TROP STORM % MO	HURR & TS MEAN	HURR & TS % MO
1919 - 23	5	52.97	6.7	12.6	0.5	7.8	0.0	0.0	0.5	7.8
1924 - 28	5	56.26	7.3	13.9	0.7	8.9	1.3	16.7	2.0	25.7
1929 - 33	5	57.47	9.1	15.8	2.1	23.1	0.5	5.7	2.6	28.8
1934 - 38	5	53.40	7.7	14.4	1.2	15.0	0.0	0.0	1.2	15.0
1939 - 43	5	54.75	7.5	13.7	0.0	0.0	0.3	4.6	0.3	4.6
1944 - 48	5	57.42	10.5	18.2	3.3	31.8	1.0	9.7	4.3	41.5
1949 - 53	5	53.63	8.1	15.1	0.8	9.5	0.0	0.0	0.8	9.5
1954 - 58	5	53.19	7.0	13.2	0.0	0.0	0.0	0.0	0.0	0.0
1959 - 63	5	56.48	9.9	17.5	1.0	10.4	0.8	6.5	1.9	18.9
1964 - 68	5	53.66	6.8	12.6	0.6	9.5	0.1	1.1	0.7	10.6
1969 - 73	5	53.23	6.3	11.8	0.0	0.0	0.5	8.0	0.5	8.0
1974 - 78	5	48.65	6.7	13.8	0.0	0.0	0.0	0.0	0.0	0.0
1919 - 48	30	55.38	8.2	14.8	1.3	15.8	0.5	6.5	1.8	22.3
1949 - 78	30	53.14	7.5	14.0	0.4	5.5	0.2	3.2	0.6	8.6
1919 - 78	60	54.26	7.8	14.4	0.9	10.9	0.4	4.9	1.2	15.8

TABLE 28

OCTOBER RAINFALL--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL MEAN RAIN	TOTAL MEAN	TOTAL % ANN	HURRICANE MEAN	HURRICANE % MO	TROP STORM MEAN	TROP STORM % MO	HURR & TS MEAN	HURR & TS % MO
1919 - 23	5	52.97	6.4	12.1	0.6	8.9	0.0	0.0	0.6	8.9
1924 - 28	5	56.26	5.6	10.0	1.5	27.3	0.0	0.0	1.5	27.3
1929 - 33	5	57.47	5.3	9.3	0.5	9.6	0.0	0.0	0.5	9.6
1934 - 38	5	53.40	4.7	8.9	0.0	0.0	0.6	12.7	0.6	12.7
1939 - 43	5	54.75	1.5	6.4	0.1	3.0	0.5	13.7	0.6	16.7
1944 - 48	5	57.42	5.7	10.0	2.6	45.3	0.2	3.4	2.8	48.7
1949 - 53	5	53.63	7.7	14.3	1.1	14.9	2.0	25.7	3.1	40.6
1954 - 58	5	53.19	4.7	8.8	0.0	0.0	0.0	0.0	0.0	0.0
1959 - 63	5	56.48	4.4	7.8	0.7	15.6	0.0	0.0	0.7	15.6
1964 - 68	5	53.66	5.7	10.6	1.1	18.6	0.0	0.0	1.1	16.6
1969 - 73	5	53.23	4.7	8.8	0.0	0.0	0.5	9.9	0.5	9.9
1974 - 78	5	48.65	2.8	5.7	0.0	0.0	0.1	5.4	0.1	5.4
1919 - 48	30	55.38	5.2	9.4	0.9	17.0	0.2	4.1	1.1	21.1
1949 - 78	30	53.14	5.0	9.4	0.5	9.7	0.4	8.7	0.9	18.3
1919 - 78	60	54.26	5.1	9.4	0.7	13.4	0.3	6.3	1.0	19.7

TABLE 29

NUMBER OF HURRICANES AND TROPICAL STORMS PER YEAR

YEAR	JUNE H	JUNE TS	JULY H	JULY TS	AUG. H	AUG. TS	SEPT. H	SEPT. TS	OCT. H	OCT. TS	OTHER H	OTHER TS	TOTAL H	TOTAL TS	TOTAL ALL
1919							1						1	0	1
1920							1		1				2	0	2
1921													0	0	0
1922													0	0	0
1923													0	0	0
1924									1				1	0	1
1925											Nov 1		0	1	1
1926			1					2	1				2	2	4
1927													0	0	0
1928					1	1	1						2	1	3
1929							1						1	0	1
1930								1					0	1	1
1931													0	0	0
1932						1							0	1	1
1933			1				2		1				4	0	4
1934				1							May 1		0	2	2
1935									2		1 Nov		3	0	3
1936		1	1			1							1	2	3
1937				1		1							0	2	2
1938										2			0	2	2
1939					1								1	0	1
1940						1							0	1	1
1941								1	1	1			1	2	3
1942													0	0	0
1943													0	0	0
1944									1				1	0	1
1945	1						1	1					2	1	3
1946									1	1			1	1	2
1947						1	1	1	1	1			2	3	5
1948							1		1				2	0	2
1949					1								1	0	1
1950							1		1				2	0	2
1951										1	1 May		1	1	2
1952											Feb 1		0	1	1
1953						1				2			0	3	3
1954													0	0	0
1955													0	0	0
1956													0	0	0
1957													0	0	0
1958													0	0	0
1959		1							1				1	1	2
1960							1	1					1	1	2
1961													0	0	0
1962						1							0	1	1
1963													0	0	0
1964		1			1		2		1				4	1	5
1965					1								1	0	1
1966	1								1				2	0	2
1967								1					0	1	1
1968		2				1			1				1	3	4
1969								1		1			0	2	2
1970								2					0	2	2
1971						1							0	1	1
1972								1					0	1	1
1973													0	0	0
1974		1								1			0	2	2
1975		1											0	1	1
1976						1							0	1	1
1977													0	0	0
1978													0	0	0
1919-48	1	1	3	2	2	6	9	6	11	5	1	2	27	22	49
1949-78	1	6	0	0	3	5	4	6	5	5	1	1	14	23	37
1919-78	2	7	3	2	5	11	13	12	16	10	2	3	41	45	86

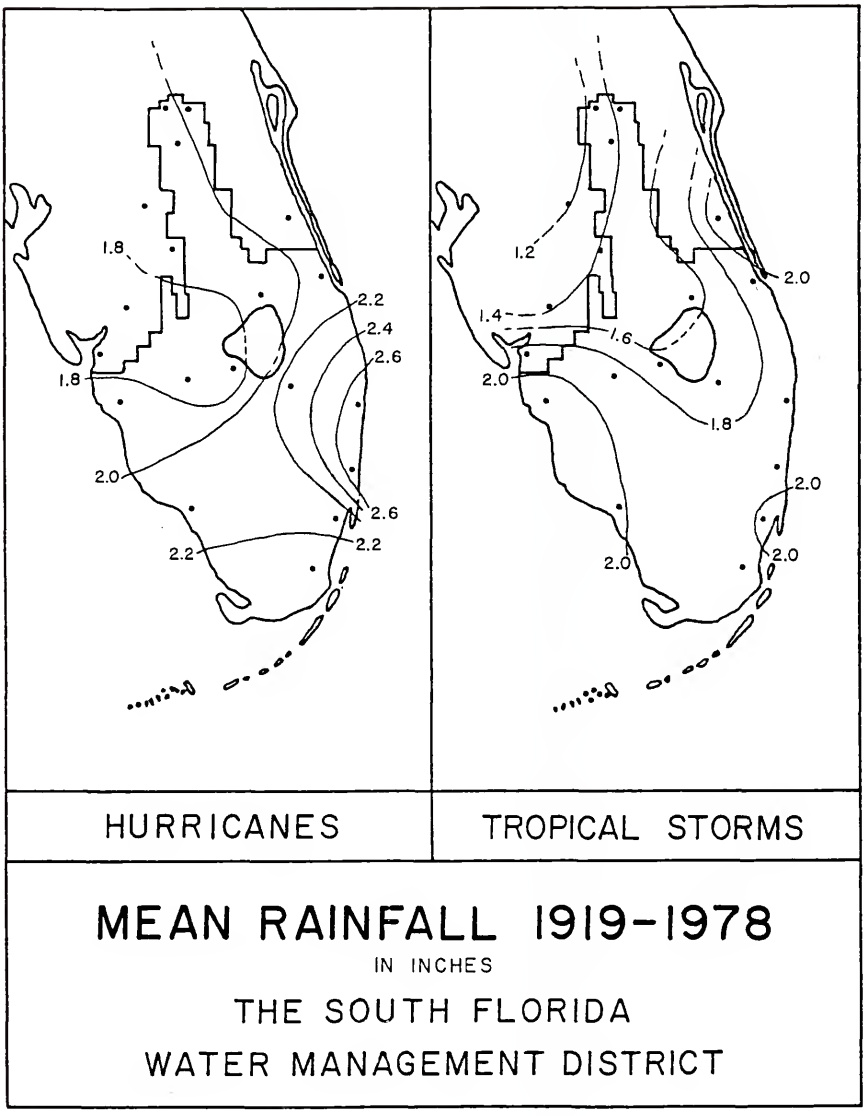

FIGURE 5

MEAN RAINFALL 1919-1978
HURRICANES AND TROPICAL STORMS

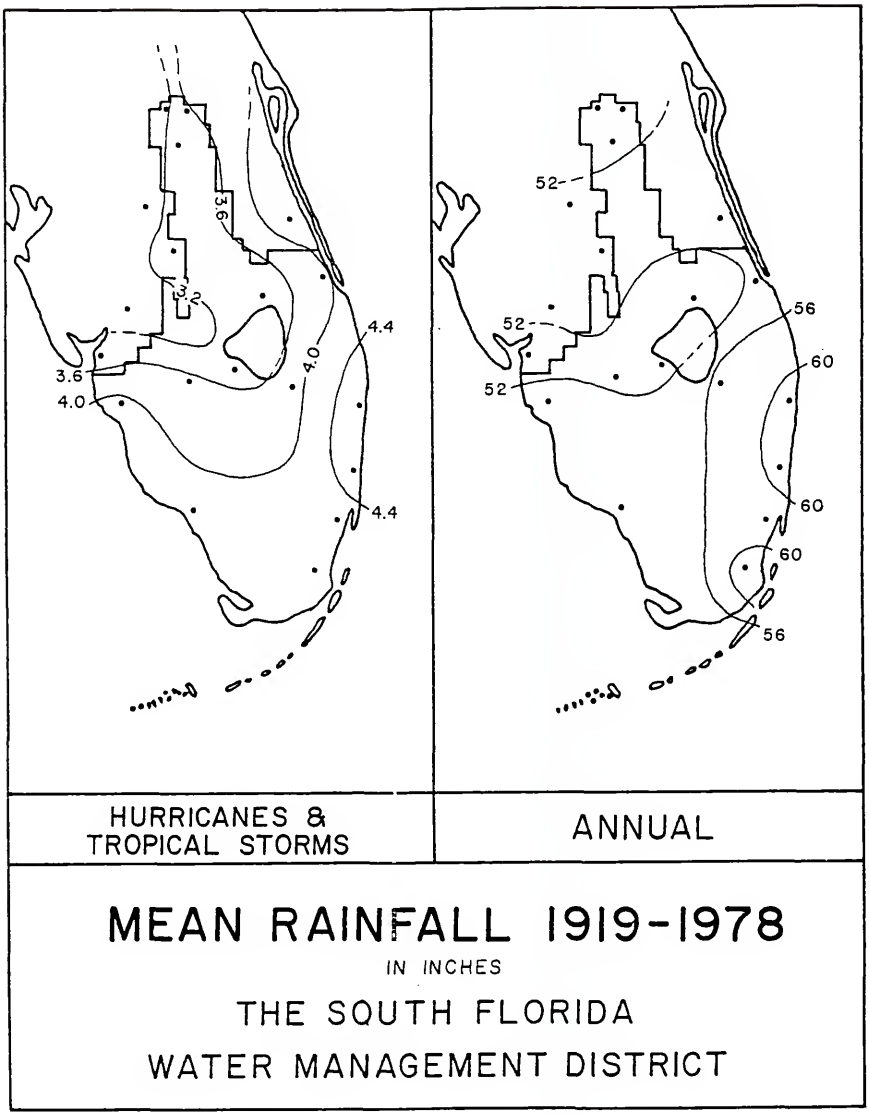

FIGURE 6

MEAN RAINFALL 1919-1978
HURRICANES & TROPICAL STORMS AND ANNUAL

inches or 15.8 percent for September and 1.0 inch or 19.7 percent for October.

The above figures correspond closely to the findings of Cry (1967) for this region for 1931 through 1960. The present study, however, provides more detail regarding South Florida. Cry treated the entire eastern and southern coasts of the United States and used data from only four stations in South Florida: Bartow, Belle Glade, Homestead, and Key West.

Although data for individual storms may at times reveal quite high amounts of rainfall, such as 12.50 inches on June 14, 1936, at Everglades City and 18.75 inches for June 14 and 15 combined at the same station, incidences of very high rainfall associated with tropical cyclones are in fact relatively rare. In most years little or no rainfall attributable to tropical cyclones falls at any given station. When years of low tropical cyclone rainfall are averaged with the years of very high rainfall, the resulting mean is far lower than the few high values would seem to indicate. The rainfall which resulted from the hurricane of June 14 and 15, 1936, equaled 34.9 percent of the sixty-year annual mean for that station and 28.6 percent of the total 65.52 inches which fell in that year. Both of these percentages are much higher than the 7.7 percent per year long term mean for combined hurricane and tropical storm rainfall at that location.

Possible Indications of Climatic Change

Examining the temporal frequency of tropical cyclones (Table 29) and the amount of rain which they have brought during each of the sixty years under study (Table 30 and Figure 7) discloses that no rain from hurricanes fell during the last ten years of the study period. A similarly long time without hurricanes occurred in the mid-1950s, including a five-year interval from 1954 through 1958 in which neither hurricanes nor tropical storms influenced the area. Another interval of low hurricane activity is found from 1937 through 1943, and a time of no tropical storms is found during the first six years of the study period.

Although temporal patterns may not be apparent to the eye, a time series analysis of rainfall, carried out by Isaacs (1980) for eight Florida cities, including three stations used in the present study, found that rainfall cycles could be identified and that peak rainfall years were closely associated with tropical weather systems. Isaacs observed cyclical periodicities for rainfall of 7.5 years for Fort Myers, 5.0 years for Fort Lauderdale, and 5.0 to 5.5 years for Orlando.

Correlations of seasonal and annual rainfall with tropical cyclone rainfall, and with number of tropical cyclones per year (Table 31) demonstrate that significant relationships can be found between the occurrence of tropical cyclones and the amount of rain which falls in a given year. Thus, if a tendency for fewer tropical systems

to strike the region can be verified, there should be a concomitant decrease in overall rainfall.

Evidence for climatic variation is found in the differences observed in mean rainfall for the first thirty years compared to the last thirty years. A t-test (Table 32) has been applied to the pairs of thirty-year samples in order to determine if the observed differences were the result of random chance. Total annual rainfall, rain from hurricanes and combined rain from hurricanes and tropical storms are all found to be significantly lower during the second thirty-year interval.

The differences between these means and the aforementioned close association between total rainfall and the occurrence of tropical systems strongly suggest that there was a tendency for less rain to fall in South Florida during the last thirty years and that the decrease is closely related to a decline in hurricane activity. The difference between the annual means for the two intervals is 2.24 inches and the difference between the hurricane season means is .96 inches. The 1.60 inch drop in rainfall from hurricanes during this period accounts for more than the amount by which seasonal rainfall declined and most of the decline in annual rainfall. The decline in hurricane rainfall was so much greater than the slight increase in tropical storm rainfall that it makes a significant decline in combined hurricane and tropical storm rainfall. A similar pattern is found for mean rain per storm (Table 33).

TABLE 30

TROPICAL CYCLONE RAINFALL BY YEAR--ALL STATIONS

DATES	NO YRS RECORD	ANNUAL TOTAL RAIN	HURR. SEASON (JUNE - OCT) TOTAL	% ANN	HURRICANE RAIN TOTAL	% ANN	% SEA	TROP. STORM RAIN TOTAL	% ANN	% SEA	HURR + TROP. ST. TOTAL	% ANN	% SEA
1919	1	55.02	28.49	51.8	0.92	1.7	3.2	0.00	0.0	0.0	0.92	1.7	3.2
1920	1	54.49	32.72	60.0	1.67	3.1	5.1	0.00	0.0	0.0	1.67	3.1	5.1
1921	1	47.13	29.89	63.4	2.66	6.1	9.6	0.00	0.0	0.0	2.66	6.1	9.6
1922	1	58.81	44.10	75.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1923	1	49.41	32.90	66.6	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1924	1	63.64	43.69	68.7	6.24	9.8	14.3	0.00	0.0	0.0	6.24	9.8	14.3
1925	1	58.36	26.33	48.5	0.00	0.0	0.0	3.56	6.1	12.6	3.56	6.1	12.6
1926	1	61.90	40.99	66.2	3.29	5.3	8.0	6.53	10.6	15.9	9.82	15.9	24.0
1927	1	39.64	30.44	76.8	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1928	1	57.78	43.71	75.6	8.18	14.2	18.7	3.16	5.5	7.2	11.34	19.6	25.9
1929	1	59.59	43.40	72.8	4.33	7.3	10.0	0.00	0.0	0.0	4.33	7.3	10.0
1930	1	66.84	38.06	56.9	0.00	0.0	0.0	2.61	3.9	6.9	2.61	3.9	6.9
1931	1	48.04	25.32	52.7	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1932	1	53.16	33.54	63.1	0.00	0.0	0.0	3.72	7.0	11.1	3.72	7.0	11.1
1533	1	59.72	41.26	69.1	12.34	20.7	29.9	0.00	0.0	0.0	12.34	20.7	29.9
1934	1	54.81	32.31	58.9	0.00	0.0	0.0	2.74	5.0	8.5	2.74	5.0	8.5
1935	1	51.57	37.11	72.0	6.53	12.7	17.6	0.00	0.0	0.0	6.53	12.7	17.6
1936	1	63.27	38.27	60.5	1.07	1.7	2.8	6.76	10.7	17.7	7.83	12.4	20.5
1937	1	56.53	35.08	62.1	0.00	0.0	0.0	2.68	4.7	7.6	2.68	4.7	7.6
1938	1	40.32	29.23	71.7	0.00	0.0	0.0	3.02	7.4	10.3	3.02	7.4	10.3
1939	1	54.14	39.94	73.8	1.75	3.2	4.4	0.00	0.0	0.0	1.75	3.2	4.4
1940	1	50.01	36.27	62.5	0.00	0.0	0.0	1.34	2.3	3.7	1.34	2.3	3.7
1941	1	60.24	34.60	57.4	0.53	0.9	1.5	4.12	6.8	11.9	4.65	7.7	13.4
1942	1	52.32	29.48	56.3	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1943	1	49.06	33.89	69.1	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1944	1	45.73	33.15	72.5	5.35	11.7	16.1	0.00	0.0	0.0	5.35	11.7	16.1
1945	1	53.65	42.74	79.7	11.00	20.5	25.7	2.56	4.8	6.0	13.56	25.3	31.7
1946	1	51.13	33.58	65.7	1.48	2.9	4.4	1.57	3.1	4.7	3.06	6.0	9.1
1947	1	78.10	52.78	67.6	8.23	10.5	15.6	4.58	5.9	8.7	12.81	16.4	24.3
1948	1	58.46	40.60	69.4	10.03	17.2	24.7	0.00	0.0	0.0	10.03	17.2	24.7
1949	1	53.81	41.08	76.3	4.53	8.4	11.0	0.00	0.0	0.0	4.53	8.4	11.0
1950	1	45.88	33.81	73.7	9.56	20.8	28.3	0.00	0.0	0.0	9.56	20.8	28.3
1951	1	50.09	35.06	70.0	0.19	0.4	0.5	4.72	9.4	13.5	4.91	5.8	14.0
1952	1	52.82	35.91	68.0	0.00	0.0	0.0	1.57	3.0	4.4	1.57	3.0	4.4
1953	1	65.32	46.12	70.6	8.00	0.2	0.0	9.21	15.4	15.1	9.21	13.4	19.1
1954	1	57.22	34.90	61.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1955	1	42.09	29.94	69.6	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1956	1	42.68	31.44	73.7	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1957	1	62.76	35.41	56.4	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1958	1	60.28	28.50	47.3	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1959	1	73.45	48.01	65.4	3.44	4.7	7.2	7.86	10.7	16.4	11.30	15.4	23.5
1960	1	65.60	46.07	70.2	5.14	7.8	11.2	4.20	6.4	9.1	9.34	14.2	20.3
1961	1	39.44	24.00	60.8	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1962	1	51.66	38.09	73.7	0.00	0.0	0.0	0.92	1.8	2.4	0.92	1.8	2.4
1963	1	52.23	29.70	56.9	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1964	1	50.12	32.00	63.9	5.03	10.0	15.7	1.96	3.9	6.1	6.99	13.9	21.8
1965	1	50.04	37.48	74.9	1.77	3.5	4.7	0.00	0.0	0.0	1.77	3.5	4.7
1966	1	60.49	39.78	65.8	4.65	7.7	11.7	0.00	0.0	0.0	4.65	7.7	11.7
1967	1	46.61	36.50	78.3	0.00	0.0	0.0	0.36	0.8	1.0	0.36	0.8	1.0
1968	1	61.03	44.22	72.5	3.10	5.1	7.0	9.26	15.2	20.9	12.35	20.2	27.9
1969	1	65.18	42.78	65.6	0.00	0.0	0.0	2.92	4.5	6.8	2.92	4.5	6.8
1970	1	50.37	28.25	56.1	0.00	0.0	0.0	1.60	3.2	5.7	1.60	3.2	5.7
1971	1	46.21	34.06	73.7	0.00	0.0	0.0	0.96	2.1	2.8	0.96	2.1	2.8
1972	1	52.18	29.02	55.6	0.00	0.0	0.0	0.33	0.6	1.1	0.33	0.6	1.1
1973	1	52.22	34.29	65.7	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1974	1	49.62	37.75	76.1	0.00	0.0	0.0	6.94	14.0	18.4	6.94	14.0	18.4
1975	1	45.37	33.22	73.2	0.00	0.0	0.0	0.53	1.2	1.6	0.53	1.2	1.6
1976	1	47.25	28.68	60.7	0.00	0.0	0.0	2.34	5.0	8.2	2.34	5.0	8.2
1977	1	48.48	30.00	61.9	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0
1978	1	52.55	31.00	59.0	0.00	0.0	0.0	0.00	0.0	0.0	0.00	0.0	0.0

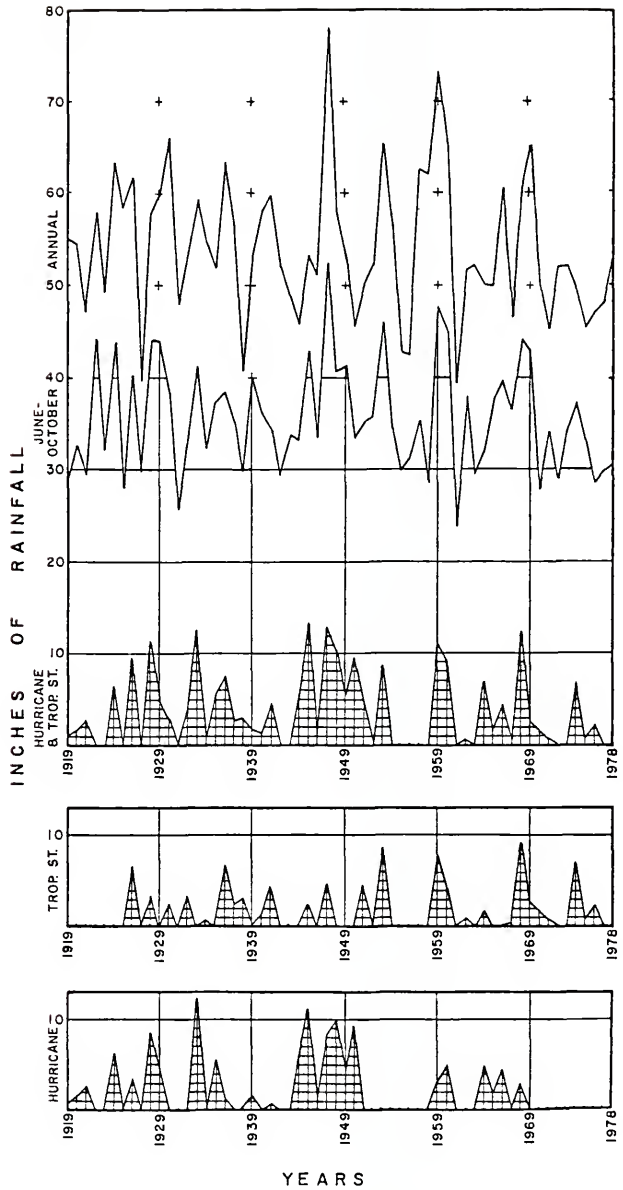

FIGURE 7
RAINFALL BY YEAR

TABLE 31

CORRELATION COEFFICIENTS

60 YEARS, 19 STATIONS

PAIR			R	R^2
ANNUAL RAIN	VS.	SEASON RAIN	0.73*	0.54
ANNUAL RAIN	VS.	HURRICANE RAIN	0.28	0.08
ANNUAL RAIN	VS.	TROPICAL STORM RAIN	0.48*	0.23
ANNUAL RAIN	VS.	HURRICANE + TROP. STORM RAIN	0.52*	0.27
SEASON RAIN	VS.	HURRICANE RAIN	0.52*	0.27
SEASON RAIN	VS.	TROPICAL STORM RAIN	0.46*	0.22
SEASON RAIN	VS.	HURRICANE + TROP. STORM RAIN	0.69*	0.48
ANNUAL RAIN	VS.	NUMBER OF HURRICANES	0.25	0.06
SEASON RAIN	VS.	NUMBER OF HURRICANES	0.39*	0.16
ANNUAL RAIN	VS.	NUMBER OF TROP. STORMS	0.37*	0.14
SEASON RAIN	VS.	NUMBER OF TROP. STORMS	0.34*	0.12
ANNUAL RAIN	VS.	NUMB. OF HURR. + TROP. STORMS	0.45*	0.29
SEASON RAIN	VS.	NUMB. OF HURR. + TROP. STORMS	0.54*	0.29

CRITICAL VALUE OF R:
at 0.05 Confidence Level = .25
at 0.01 Confidence Level = .33

* = Sig. at 0.01 Level
All are significant at 0.05 Level

TABLE 32

t-TESTS OF RAINFALL DATA--ALL STATIONS

	1919 - 48 MEAN	1919 - 48 S.D.	1949 - 78 MEAN	1949 - 78 S.D.	t
ANNUAL	55.38	7.72	53.14	8.00	3.07*
SEASONAL	36.20	6.19	35.24	6.03	1.51
HURRICANE	2.06	3.81	1.25	2.37	4.06*
TROP. ST.	1.63	2.07	1.84	2.86	-0.48
HURR. + T.S.	4.49	4.22	3.09	3.89	2.76*

CRITICAL VALUES OF t:
0.05 Confidence Level = 2.04
0.01 Confidence Level = 2.75

* = Significant at .01 Level

TABLE 33

INCHES OF RAINFALL PER TROPICAL CYCLONE

	1919-48	1949-78	1919-78
HURR. RAIN / NO. OF STORMS	3.18	2.55	3.00
TR. ST. RAIN / NO. OF STORMS	2.33	2.40	2.37
HURR. + T.S. / NO. OF STORMS	2.61	2.51	2.63

Rainfall per hurricane has declined while rainfall per tropical storm has risen but by a lesser amount.

Hebert (1980) has observed that in the absence of tropical weather systems, other atmospheric conditions, such as a shift in upper air currents, may produce periods of rainfall greater than that which occurs during years of tropical cyclones. This research has shown Hebert's statement to be correct although it is also valid to state that years in which tropical cyclones strike generally tend to be wetter than years when the great storms do not influence the region.

Paradoxically, although years of tropical cyclone activity tend to be wetter than years without the great storms, the principal difference in rainfall seems to be during the non-hurricane season months. In spite of statistically significant drops in hurricane rainfall and combined hurricane and tropical storm rainfall during the second half of the study period, hurricane season rainfall did not decline significantly. Thus, Hebert's observation of other causes taking the place of tropical cyclone rainfall may be true during hurricane season but perhaps not acceptable for the entire year. This finding may be a clue to evidence which could link the occurrence of tropical cyclone activity with other features of the atmosphere which may be associated with rainfall during the months of November through May. The observation of such complexities in the mechanisms which influence weather is another example

of why it is important to know in advance what effects weather modification may have and how difficult it is to ascertain those effects.

CHAPTER 6

WATER FROM TROPICAL CYCLONE RAINFALL

Only part of the water that falls as rain can be saved for later use. Some rainfall infiltrates the ground immediately while the remainder may be ponded for several days before soaking in or stay on the surface until it flows out of the area or evaporates. Some water that soaks into the ground will return to the surface as seepage into lakes and streams or may pass directly to the atmosphere by evapotranspiration.

Estimates of the amount of water available from tropical cyclones are obtained by multiplying the depth of rainfall from these storms by the areas of polygons which have been defined around each weather station, and calculating how much of the total water could have entered the ground or remained in surface storage in each polygon. An estimated quantity of water that would be lost to evapotranspiration is then deducted from the sum of ground and surface water storage in order to obtain the net amount of new water available from hurricanes and tropical storms for a year of average rainfall.

Methodology for Estimating Infiltration

Many factors affect the rate and volume of infiltration. Some of the more important considerations are topography, ground cover, porosity, permeability, and the amount of water already occupying potential storage space. Numerical models have been designed to estimate the amount of runoff that occurs in specific watersheds, including some parts of the South Florida Water Management District (Shahane, Berger, & Hamrick, 1977), (Shahane & Hamrick, 1974), (Shih, 1976). No comprehensive model of infiltration is available, however, for the Water Management District, therefore, empirical data are used to obtain direct estimates of the amount of increased groundwater storage resulting from tropical cyclone rainfall.

The procedure for estimating the amount of infiltration from tropical cyclones is that of determining soakage rates based upon the relationships between sets of paired data for rainfall and rise of water level in observation wells, and applying those rates to historical rainfall data per storm. Mean depth of the water table is used as a maximum limit to the amount of groundwater rise allowable for the rainfall from each storm and perennial wetlands are assumed to accommodate no increased groundwater storage.

For the purpose of estimating the areas over which given depths of water were spread, the South Florida Water Management District was divided into nineteen regions

(Figure 8, Table 34) based upon the weather stations used in the earlier part of this study. Each region is a polygon that is drawn so that any point within it is closer to the weather station in its area than to any other station (Theissen, 1911). Rainfall from hurricanes and tropical storms is assumed to extend uniformly across the area and a mean soakage rate is calculated for each polygon.

Water level data from 55 wells (USGS, 1976-1978) (SFWMD, 1981) are used (Figure 8, Table 35). Data from some wells located near polygon boundaries are used to calculate infiltration for two or three polygons. No satisfactory well data could be obtained for two polygons with very small dry areas along the edge of the Water Management District. Infiltration estimates for these areas, in the vicinities of Bartow and Punta Gorda, use the mean soakage function for two other nearby polygons.

Initial plans called for subdividing the polygons into smaller areas around each well site based upon differences in ground porosity. This was not possible because no porosity data were available. According to Kreitman (1981), Director of Groundwater Division, SFWMD, the porosity of these wells has not been studied. Kreitman also commented that if such data were available they would yield misleading results because the antecedent moisture conditions above the water table before each storm would not be known. He stated that the South Florida Water Management District and the United States Army Corps of Engineers have found that one

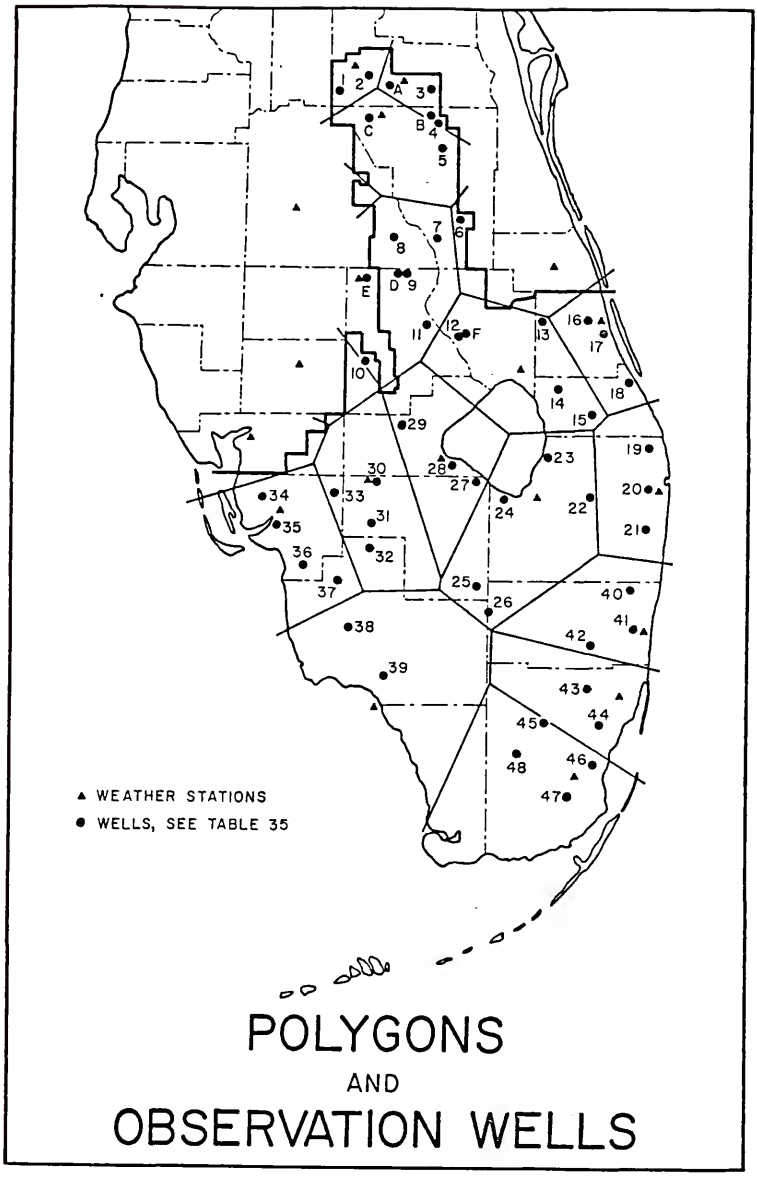

FIGURE 8

POLYGONS AND OBSERVATION WELLS

TABLE 34

POLYGON SPECIFICATIONS

POLYGON NAME	TOTAL AREA SQ MI	DRY AREA SQ MI	IMPOUND-ABLE SQ MI	DEPTH TO WATER FEET	MAX. INTER. STORAGE FEET	STORAGE FUNCTION	EVAPO-TRANS %
ARCADIA	116	2	116.0	3.040	0.641	Y = -.008 + .488 X	96.2
AVON PARK	843	597	843.0	3.622	0.605	Y = -.013 + .756 X	94.0
BARTOW	38	32	38.0	3.622	0.605	Y = -.008 + .697 X	89.4
BELLE GLADE	1735	732	1474.6	3.494	0.583	Y = .049 + .187 X	83.1
EVERGLADES CITY	1616	79	0.0	3.173	0.530	Y = .035 + .336 X	100.0
FELLSMERE	309	138	231.8	6.176	1.031	Y = -.002 + .441 X	85.7
FORT LAUDERDALE	924	433	462.0	5.613	0.937	Y = .038 + .421 X	82.5
FORT MYERS	804	357	0.0	19.528	3.261	Y = -.045 + .864 X	100.0
FORT PIERCE	563	311	0.0	8.543	1.427	Y = .042 + .266 X	92.8
HOMESTEAD	1251	281	125.1	5.515	0.921	Y = .022 + .351 X	86.8
ISLEWORTH	171	125	171.0	21.673	3.620	Y = -.604 + .639 X	93.0
KISSIMMEE	821	540	821.0	21.636	3.620	Y = .036 + .209 X	96.1
LA BELLE	1331	27	166.3	4.057	0.677	Y = -.016 + .425 X	93.2
MIAMI	756	268	367.8	3.855	0.510	Y = .020 + .235 X	90.4
MOORE HAVEN	1061	283	819.2	1.600	0.267	Y = .003 + .623 X	98.0
OKEECHOBEE	1335	561	934.5	6.364	1.063	Y = .070 + .334 X	100.0
ORLANDO	159	124	159.0	41.915	7.000	Y = .004 + .651 X	93.9
PUNTA GORDA	97	15	0.0	3.009	0.501	Y = -.012 + .456 X	100.0
WEST PALM BEACH	760	374	99.8	5.154	0.861	Y = .027 + .349 X	81.3

TABLE 35

OBSERVATION WELL INDEX

No.	POLYGON (north to south)	LATITUDE deg	min	sec	LONGITUDE deg	min	sec	NEARBY TOWN OR FEATURE
1	Isleworth	28	22	02	81	38	46	Lake Buena Vista
2	"	28	25	56	81	30	24	Windermere
3	Orlando	28	25	31	81	09	57	Bee Line Expressway
4	"	28	17	14	81	09	30	Pine Grove
5	Kissimmee	28	11	41	81	09	41	St. Cloud
6	Fellsmere	27	48	28	81	01	09	Kenansville
7	Avon Park	27	46	46	81	07	48	State Road 60
8	"	27	46	12	81	19	03	State Roads 60 & 630
9	"	27	37	51	81	15	56	Highlands & Polk Co. line
10	"	27	16	11	81	24	57	Lake Placid
11	"	27	25	04	81	12	01	U. S. Highway 98
12	Okeechobee	27	23	15	81	01	09	Basinger
13	"	27	26	55	80	40	16	State Road 66
14	"	27	09	51	80	33	55	State Road 710
15	"	27	01	03	80	26	24	Indian Town
16	Fort Pierce	27	25	24	80	24	26	Fort Pierce
17	"	27	23	13	80	18	27	Fort Pierce
18	"	27	10	10	80	14	12	Palm Harbor
19	West Palm Beach	26	52	58	80	05	44	Juno
20	"	26	41	23	80	05	38	West Palm Beach
21	"	26	33	28	80	08	52	Boynton Beach
22	Belle Glade	26	40	05	80	23	35	U. S. Highways 98 & 441
23	"	26	52	40	80	37	21	Canal Point
24	"	26	41	53	80	47	52	Lake Harbor
25	"	26	18	59	80	58	54	Big Cypress Indian Res.
26	"	26	10	00	80	52	00	Alligator Alley
27	Moore Haven	26	45	07	80	54	17	Clewiston
28	"	26	48	59	81	00	51	Moore Haven
29	"	27	01	57	81	20	31	Palm Dale
30	La Belle	26	45	27	81	26	19	La Belle
31	"	26	33	10	81	25	09	Felda
32	"	26	27	24	81	26	07	Immokalee
33	"	26	42	53	81	35	54	Lehigh Acres
34	Fort Myers	26	39	03	81	55	04	North Fort Myers
35	"	26	33	23	81	52	24	Fort Myers
36	"	26	20	42	81	45	50	Bonita Springs
37	"	26	18	02	81	34	40	County Road 846
38	Everglades	26	06	32	81	32	47	Alligator Alley
39	"	25	57	48	81	18	18	Ochopee
40	Fort Lauderdale	26	17	10	80	13	50	Pompano Beach
41	"	26	06	57	80	12	23	Fort Lauderdale
42	"	26	00	25	80	23	04	U. S. Highway 27
43	Miami	25	52	08	80	27	40	Pennsuco
44	"	25	42	02	80	23	26	Kendall
45	"	25	45	00	80	36	00	U. S. Highway 41
46	Homestead	25	32	58	80	26	43	South Miami Heights
47	"	24	24	25	80	32	00	Florida City
48	"	25	40	00	80	40	00	Everglades Nat. Park

COMBINATION WELL AND RAIN GUAGE INSTALLATIONS

A	Orlando	28	25	81	22	Taft
B	"	28	19	81	09	Lake Myrtle
C	Kissimmee	28	17	81	28	Kissimmee
D	Avon Park	27	37	81	15	Lake Lotella
E	"	27	35	81	22	Avon Park
F	Okeechobee	27	23	81	02	Basinger
G	West Palm Beach	26	39	80	05	West Palm Beach

inch of water will occupy about six inches in the ground. This one-to-six ratio indicates that newly infiltrated water occupies only about seventeen percent of the ground volume in a region that Kreitman estimates to have an average porosity between twenty and thirty percent.

Initial research design also specified that tropical cyclone rainfall data compiled earlier would be used to compute infiltration rates. Very little of those data are useful for this operation, however, because records for most observation wells begin in the early to mid-1970's, allowing little overlap between the times of tropical cyclone rainfall in South Florida and the time for which well data are available.

The rainfall data used to compute infiltration rates are of two types. First, times of widespread heavy rainfall emanating from large weather systems are used. Because of the distances between many wells and the nearest rainfall gauge, only storms which dropped rain over large contiguous areas can be used and isolated thunder showers are avoided. This information is supplemented by data from combination well and rain gauge installations where well level and rainfall are recorded continuously on the same roll of paper. Data of this type, however, are available for only a small part of the Water Management District.

An S-shaped soakage function was expected because small amounts of rain would be insufficient to penetrate to the water table and very large amounts of rain would saturate

the ground so that no additional water could be stored. The data, however, do not indicate an S-shaped curve. Scattergrams of paired rainfall and well data for all polygons and for combination sites indicate a linear increase in the amount of soakage associated with increased rainfall: therefore, linear regression is used to calculate infiltration rates.

Methodology for Estimating Impoundable Surface Water

Certain parts of the South Florida Water Management District contain dikes which enclose reservoirs that are used to store surface water. These consist primarily of Lake Okeechobee and three Conservation Areas southeast of the lake (Storch, 1973). Any rain which falls on to one of these reservoirs or their watersheds could potentially be caught and stored in these or other closed depressions at upstream locations, if the available storage capacity is not already full. Outside of these areas, most rain falls in places where it is not feasible to retain large quantities of water for later use or in locations from which it cannot be transported to areas where it may be needed.

In order to estimate the amount of impoundable surface water, the area of the reservoirs and their contributing watersheds is measured for each polygon and the resulting figure is multiplied by the depth of rainwater per storm which fell at the central weather station for that polygon.

infiltration which would have occurred in the dry parts of the watersheds is then deducted, so that only runoff and ponded water are included in the net impoundable surface water total. It is assumed that adequate storage capacity will be available to retain all of this water, but there may be times during very wet seasons when all reservoirs will be full and any new increment of rainfall will have to be allowed to flow freely to the sea.

Methodology for Estimating Evapotranspiration

Rates of evapotranspiration vary greatly, depending on numerous factors such as temperature, intensity of sunlight, humidity, cloud cover, ground cover, windspeed, growth cycles of vegetation, and the amount of moisture available (Storch, 1972). It is not possible to account for all of the variations which might occur in different parts of the study area at any given time. Generalized estimates of average evapotranspiration are therefore used. These estimates are obtained by dividing potential annual evapotranspiration (Visher & Hughes, 1969) by mean annual rainfall to determine the percentage of moisture which would be lost to this cause during an average year. It is assumed that these rates apply equally to all rainwater that falls during the year regardless of time or source.

Estimates of Water from Tropical Cyclone Rainfall

Analysis of various aspects of the amount of water available from hurricane and tropical storm rainfall (Tables 36 and 37) show that after runoff and evapotranspiration are considered, relatively little water remains for human consumption. Some polygons have very small perennially dry surface areas and much of the Water Management District has only a few feet of storage space between the water table and the ground surface. Water remaining in the ground and on the surface after the storm has passed is subject to high evapotranspiration rates and is depleted naturally with the passing of time, without human consumption. Although under ideal conditions, given the rainfall of 1919 through 1948, it may be possible to save 428,590 acre feet of hurricane rainfall per year in the ground and 774,100 acre feet in surface reservoirs, if that water is not used in one year, only 102,300 acre feet will remain. Using rainfall data from 1949 through 1978, only 74,270 acre feet would remain after one year.

Estimates of rainwater per polygon reveal that the areal distribution of water which is available for human use after the passage of a hurricane or tropical storm, is not the same as the distribution of storm rainfall. Some polygons may receive very little infiltration, and several which have no impoundable area are considered to have no increase in surface storage, even though some may occur.

TABLE 36

WATER FROM HURRICANE RAINFALL

(ACRE FEET x 1,000)

POLYGON NAME	DATES	TOTAL		INFILTRATION		IMPOUNDABLE SURFACE WATER		INFILTRATION & IMP SURFC		INFILT & SURFC MINUS EVAP	
		TOTAL	ANNUAL	TOTAL	ANNUAL	TOTAL	ANNUAL	TOTAL	ANNUAL	TOTAL	ANNUAL
ARCADIA	1919 - 48	385.1	12.0	2.96	0.10	382.16	12.74	385.12	12.84	14.63	0.49
	1949 - 78	207.1	6.9	1.60	0.05	205.53	6.85	207.13	6.90	7.07	0.26
	1919 - 78	592.2	9.9	4.56	0.08	587.69	9.79	592.25	9.87	22.51	0.38
AVON PARK	1919 - 48	3551.4	110.4	1765.08	58.24	1786.31	59.54	3551.39	118.38	340.93	11.36
	1949 - 78	1723.3	57.4	853.10	28.44	870.21	29.01	1723.32	57.44	165.44	5.51
	1919 - 78	5274.7	87.9	2618.19	43.64	2656.52	44.28	5274.71	87.91	506.37	8.44
BARTOW	1919 - 48	159.0	5.3	83.96	2.80	75.01	2.50	158.97	5.30	16.85	0.56
	1949 - 78	67.6	2.3	37.39	1.25	30.22	1.01	67.61	2.25	7.17	0.24
	1919 - 78	226.6	3.8	121.35	2.02	105.24	1.75	226.58	3.78	24.02	0.40
BELLE GLADE	1919 - 48	8499.2	283.3	1290.35	43.01	5933.96	197.80	7224.31	240.81	783.45	26.25
	1949 - 78	3954.9	131.8	633.40	21.11	2728.24	90.94	3361.64	112.05	366.42	12.21
	1919 - 78	12454.1	207.6	1923.75	32.06	8662.21	144.37	10586.00	176.43	1153.87	19.23
EVERGLADES CITY	1919 - 48	8505.8	283.5	187.49	6.25	0.00	0.00	187.49	6.25	0.00	0.00
	1949 - 78	2562.3	85.4	66.86	2.23	0.00	0.00	66.86	2.23	0.00	0.00
	1919 - 78	11068.1	184.5	254.36	4.24	0.00	0.00	254.36	4.24	0.00	0.00
FELLSMERE	1919 - 48	1468.5	49.0	284.46	9.48	1050.20	35.01	1334.66	44.49	190.86	6.36
	1949 - 78	632.2	21.1	122.03	4.07	452.16	15.07	574.20	19.14	82.11	2.74
	1919 - 78	2100.7	35.0	406.49	6.77	1502.36	25.04	1908.86	31.81	272.97	4.55
FORT LAUDERDALE	1919 - 48	5775.1	192.5	1423.60	47.46	2687.56	96.25	4311.24	143.71	754.47	25.15
	1949 - 78	2236.8	74.6	588.72	19.62	1118.41	37.28	1707.13	56.90	298.75	9.96
	1919 - 78	8011.9	133.5	2012.40	33.54	4005.97	66.77	6018.37	100.31	1053.22	17.55
FORT MYERS	1919 - 48	3988.6	133.0	1114.11	37.14	0.00	0.00	1114.11	37.14	0.00	0.00
	1949 - 78	1346.5	44.9	325.89	10.86	0.00	0.00	325.89	10.86	0.00	0.00
	1919 - 78	5335.1	88.9	1440.00	24.00	0.00	0.00	1440.00	24.00	0.00	0.00
FORT PIERCE	1919 - 48	2485.9	82.9	590.99	19.70	0.00	0.00	590.99	19.70	42.55	1.42
	1949 - 78	1221.2	40.7	296.47	9.88	0.00	0.00	296.47	9.88	21.35	0.71
	1919 - 78	3707.1	61.8	887.46	14.79	0.00	0.00	887.46	14.79	63.90	1.06
HOMESTEAD	1919 - 48	6593.9	219.8	626.70	20.89	659.39	21.98	1286.10	42.87	169.76	5.66
	1949 - 78	2703.5	90.1	268.54	8.95	270.35	9.01	538.89	17.96	71.13	2.37
	1919 - 78	9297.4	155.0	895.24	14.92	929.74	15.50	1824.98	30.42	240.90	4.01
ISLEWORTH	1919 - 48	637.6	21.3	289.18	9.64	348.40	11.61	637.58	21.25	44.63	1.49
	1949 - 78	421.7	14.1	192.50	6.42	229.21	7.64	421.71	14.06	29.52	0.98
	1919 - 78	1059.3	17.7	481.60	8.03	577.61	9.63	1059.29	17.65	74.15	1.24
KISSIMMEE	1919 - 48	3416.7	113.9	1291.01	43.03	2125.67	70.86	3416.67	113.89	133.25	4.44
	1949 - 78	1765.0	58.8	668.50	22.28	1096.55	36.55	1765.04	58.83	68.84	2.29
	1919 - 78	5181.7	86.4	1959.50	32.66	3222.21	53.70	5181.71	86.36	202.09	3.37
LA BELLE	1919 - 48	5813.1	193.6	42.65	1.42	809.14	26.97	851.79	28.39	6.81	0.23
	1949 - 78	1704.4	56.8	10.82	0.36	237.42	7.91	248.25	8.27	1.99	0.07
	1919 - 78	7517.5	125.3	53.48	0.89	1046.57	17.44	1100.04	18.33	8.80	0.15
MIAMI	1919 - 48	3132.1	104.4	379.93	12.66	1440.75	48.02	1820.67	60.69	174.78	5.83
	1949 - 78	2021.2	67.4	232.56	7.75	929.77	30.99	1162.33	38.74	111.58	3.72
	1919 - 78	5153.3	85.9	612.49	10.21	2370.52	39.51	2983.00	49.72	286.37	4.77
MOORE HAVEN	1919 - 48	3922.2	130.7	589.16	19.64	2352.46	78.42	2941.62	98.05	58.83	1.96
	1949 - 78	1617.2	60.6	297.46	9.92	1065.47	35.52	1362.92	45.43	27.26	0.91
	1919 - 78	5733.4	95.7	866.62	14.70	3417.93	56.97	4304.54	71.74	86.09	1.43
OKEECHOBEE	1919 - 48	5715.2	190.5	1550.30	51.94	2442.36	81.41	4000.66	133.36	0.00	0.00
	1949 - 78	2230.0	74.3	705.06	23.50	855.33	28.53	1560.99	52.03	0.00	0.00
	1919 - 78	7945.2	132.4	2263.36	37.72	3298.29	54.97	5561.65	92.69	0.00	0.00
ORLANDO	1919 - 48	689.1	23.0	358.42	11.95	330.67	11.02	689.08	22.97	42.03	1.40
	1949 - 78	368.0	12.3	191.29	6.38	176.74	5.89	368.03	12.27	22.45	0.75
	1919 - 78	1057.1	17.6	549.71	9.16	507.41	8.46	1057.12	17.62	64.48	1.07
PUNTA GORDA	1919 - 48	352.1	11.7	21.72	0.72	0.00	0.00	21.72	0.72	0.00	0.00
	1949 - 78	169.8	5.7	10.36	0.35	0.00	0.00	10.36	0.35	0.00	0.00
	1919 - 78	521.9	8.7	32.08	0.53	0.00	0.00	32.08	0.53	0.00	0.00
WEST PALM BEACH	1919 - 48	4608.0	153.6	957.65	31.92	599.04	19.97	1556.69	51.89	291.10	9.70
	1949 - 78	1580.2	52.7	359.05	11.97	205.43	6.85	564.48	18.82	105.56	3.52
	1919 - 78	6188.2	103.1	1316.70	21.94	804.47	13.41	2121.17	35.35	396.66	6.61
TOTAL	1919 - 48	69698.5	2323.3	*12857.80	428.59	*23223.10	774.10	36080.90	1202.70	3068.96	102.30
	1949 - 78	28733.1	957.8	5661.62	195.39	*10471.60	349.05	16333.30	544.44	1387.43	46.25
	1919 - 78	98431.6	1640.5	*18719.40	311.99	*33694.70	561.58	52414.10	873.57	4456.38	74.27

See note following Table 37.

TABLE 37

WATER FROM TROPICAL STORM RAINFALL

(ACRE FEET x 1,000)

POLYGON NAME	DATES	TOTAL		INFILTRATION		IMPOUNDAGLF SURFACE WATER		INFILTRATION & IMP SURFC		INFILT & SURFC MINUS EVAP	
		TOTAL	ANNUAL	TOTAL	ANNUAL	TOTAL	ANNUAL	TOTAL	ANNUAL	TOTAL	ANNUAL
AACADIA	1919 - 48	211.9	7.1	1.56	0.05	210.32	7.01	211.88	7.06	8.05	0.27
	1949 - 78	297.5	9.9	2.27	0.08	295.25	9.84	297.52	9.92	11.31	0.38
	1919 - 78	509.4	8.5	3.05	0.06	505.56	8.43	509.41	8.49	19.36	0.32
AVON PARK	1919 - 48	1490.9	49.7	698.85	23.30	792.02	26.40	1490.87	49.70	143.12	4.77
	1949 - 78	2296.6	76.6	1101.57	36.72	1194.98	39.83	2296.56	76.55	220.47	7.35
	1919 - 78	3787.4	63.1	1800.43	30.01	1987.00	33.12	3787.43	63.12	363.59	6.06
BARTOW	1919 - 48	78.5	2.6	42.77	1.43	35.68	1.19	78.45	2.62	8.32	0.28
	1949 - 78	65.8	2.2	34.06	1.16	30.95	1.03	65.81	2.19	6.98	0.23
	1919 - 78	144.3	2.4	77.63	1.29	66.63	1.11	144.26	2.40	15.29	0.25
BELLE GLADE	1919 - 48	4517.5	150.6	815.52	27.18	3024.34	100.81	3839.86	128.00	418.54	13.95
	1949 - 78	4912.6	163.8	915.56	30.52	3260.15	108.67	4175.71	139.19	455.15	15.17
	1919 - 70	9430.1	157.2	1731.08	28.85	6284.46	104.74	8015.56	133.59	873.70	14.56
EVERGLADES CITY	1919 - 48	6169.2	205.6	135.21	4.51	0.00	0.00	135.21	4.51	0.00	0.00
	1949 - 78	4063.7	135.5	107.45	3.58	0.00	0.00	107.45	3.58	0.00	0.00
	1919 - 78	10232.9	170.5	242.66	4.04	0.00	0.00	242.66	4.04	0.00	0.00
FELLSMERE	1919 - 48	981.9	33.1	191.83	6.39	709.42	23.65	901.25	30.04	128.88	4.30
	1949 - 78	1163.5	38.8	225.09	7.50	832.10	27.74	1057.19	35.24	151.18	5.04
	1919 - 78	2155.4	35.9	416.92	6.95	1541.52	25.69	1958.44	32.64	280.06	4.67
FORT LAUDERDALE	1919 - 48	2731.1	91.0	749.42	24.98	1365.55	45.52	2114.97	70.50	370.12	12.34
	1949 - 78	3047.0	101.6	843.33	28.11	1523.49	50.78	2366.82	78.89	414.19	13.81
	1919 - 78	5778.1	96.3	1592.75	26.55	2889.04	48.15	4481.79	74.70	784.31	13.07
FORT MYERS	1919 - 48	2822.2	94.1	779.10	25.97	0.00	0.00	779.10	25.97	0.00	0.00
	1949 - 78	3351.7	111.7	932.99	31.10	0.00	0.00	932.99	31.10	0.00	0.00
	1919 - 78	6173.9	102.9	1712.09	28.53	0.00	0.00	1712.09	28.53	0.00	0.00
FORT PIERCE	1919 - 48	1747.3	58.2	423.93	14.13	0.00	0.00	423.93	14.13	30.52	1.02
	1949 - 78	1702.5	56.8	442.44	14.75	0.00	0.00	442.44	14.75	31.66	1.06
	1919 - 78	3449.8	57.5	866.37	14.44	0.00	0.00	866.37	14.44	62.18	1.04
HOMESTEAD	1919 - 48	3081.1	129.4	385.12	12.84	388.11	12.94	773.23	25.77	102.07	3.40
	1949 - 78	3330.0	111.0	353.54	11.76	333.00	11.10	686.54	22.88	90.62	3.02
	1919 - 78	7211.1	120.2	738.66	12.31	721.11	12.02	1459.77	24.33	192.69	3.21
ISLEWORTH	1919 - 48	305.8	10.2	136.44	4.55	169.36	5.65	305.79	10.19	21.41	0.71
	1949 - 78	379.8	12.7	170.07	5.67	209.78	6.99	379.85	12.66	26.55	0.89
	1919 - 78	685.6	11.4	306.51	5.11	379.13	6.32	685.64	11.43	47.95	0.80
KISSIMMEE	1919 - 48	1440.6	48.0	804.20	26.81	636.38	21.21	1440.58	48.02	56.18	1.87
	1949 - 78	2078.1	69.3	983.63	32.79	1094.49	36.48	2078.12	69.27	81.05	2.70
	1919 - 78	3518.7	58.6	1787.83	29.80	1730.87	28.85	3518.70	58.64	137.23	2.29
LA BELLE	1919 - 48	4042.7	134.8	29.32	0.98	562.75	18.76	592.07	19.74	4.74	0.16
	1949 - 78	3884.4	129.5	27.13	0.90	540.83	18.03	567.96	18.93	4.54	0.15
	1919 - 78	7927.1	132.1	56.45	0.94	1103.58	18.39	1160.03	19.33	9.28	0.15
MIAMI	1919 - 48	2254.7	75.2	275.58	9.19	1037.16	34.57	1312.74	43.76	126.02	4.20
	1949 - 78	2736.9	91.2	329.81	10.99	1258.98	41.97	1588.79	52.96	152.52	5.08
	1919 - 78	4991.6	83.2	605.38	10.09	2296.14	38.27	2901.53	48.36	278.55	4.64
MOORE HAVEN	1919 - 48	2616.9	87.2	428.07	14.30	1533.59	51.12	1962.66	65.42	39.25	1.31
	1949 - 78	3027.4	100.9	444.20	14.81	1826.33	60.88	2270.53	75.68	45.41	1.51
	1919 - 78	5644.3	94.1	873.27	14.55	3359.92	56.00	4233.20	70.55	84.66	1.41
OKEECHOBEE	1919 - 48	2765.9	93.0	951.54	31.72	1000.69	33.36	1952.23	65.07	0.00	0.00
	1949 - 78	3935.3	131.2	1196.55	39.88	1553.61	51.95	2755.16	91.84	0.00	0.00
	1919 - 78	6724.8	112.1	2148.09	35.80	2559.30	42.66	4707.39	78.46	0.00	0.00
ORLANDO	1919 - 48	352.9	11.8	135.53	6.18	167.40	5.58	352.94	11.76	21.53	0.72
	1949 - 78	437.5	14.6	229.41	7.65	208.07	6.94	437.48	14.58	26.69	0.89
	1919 - 78	790.4	13.2	414.95	6.92	375.48	6.26	790.42	13.17	48.22	0.80
PUNTA GORDA	1919 - 48	260.3	8.7	16.05	0.53	0.00	0.00	16.05	0.53	0.00	0.00
	1949 - 78	314.8	10.5	19.55	0.65	0.00	0.00	19.55	0.65	0.00	0.00
	1919 - 78	575.1	9.6	35.60	0.59	0.00	0.00	35.60	0.59	0.00	0.00
WEST PALM BEACH	1919 - 48	2021.8	67.4	472.07	15.76	262.83	8.76	735.70	24.52	137.58	4.59
	1949 - 78	2628.8	87.6	595.42	19.05	341.75	11.39	937.17	31.24	175.25	5.84
	1919 - 78	4650.6	77.5	1068.29	17.80	604.58	10.08	1672.87	27.88	312.63	5.21
TOTAL	1919 - 48	40726.1	1357.5	7523.94	250.80	11895.60	396.52	19419.50	647.32	1616.33	53.88
	1949 - 78	43654.5	1455.1	8954.66	298.50	14508.80	483.63	23463.60	782.12	1893.80	63.13
	1919 - 78	84360.6	1406.1	16478.80	274.65	26404.40	440.07	42883.20	714.72	3510.14	58.50

See note on following page.

Note Regarding Tables 36 and 37

"TOTAL" is the total amount of water from hurricane rainfall. It is determined by converting the rainfall depth from inches to feet and multiplying that quotient by the area in acres.

"INFILTRATION" indicates the estimated amount of water which entered the ground. It is calculated by applying the soakage function to the rainfall depth and multiplying that product by the area of dry land surface in acres. This value is not allowed to exceed the maximum storage possible within the space between the ground surface and the mean water table. Dry areas were identified by topographical maps, Landsat remote sensing imagery and U-2 aerial photographs at the scale 1:250,000.

"IMPOUNDABLE SURFACE WATER" is an estimate of the amount of runoff that could be impounded in existing reservoirs if other water was not already occupying the necessary space. It is calculated by multiplying the rainfall in feet by the area of Lake Okeechobee, the three Conservation Areas, and all of the area which drains into these reservoirs (Figure 9), and deleting infiltration which would occur in the dry parts of these areas.

"INFILTRATION & IMP SURFC" is the sum of two preceding columns. It is an estimate of the total water that could be retained after initial runoff from storm.

"INFILT & SURFC MINUS EVAP" is the net water remaining in the ground and on the surface after a year of evapotranspiration. Evapotranspiration rates are taken from Visher and Hughes (1969).

Using the procedures described above, all of the increase in surface storage (Figure 9) and much of the added ground water are found at inland locations in the central and northern parts of the Water Management District, while rainfall (Figures 5 and 6) is more evenly distributed, with the greatest quantities falling along the southeastern coast.

When the rainfall data are converted from unidimensional depths (Tables 4 through 20) to volumetric measurements (Tables 36 and 37), the close relationship between rainfall and water supply becomes apparent. The rainfall from hurricanes for the second half of the study period was only 44 percent of that for the first half. Although the total water from hurricanes declined by a greater proportion, to 41 percent of the earlier total, infiltration and impoundable runoff declined slightly less, to 44 and 45 percent, because of changes in the areal distribution of rainfall between the two intervals.

The percentage of rainfall from all sources, which would be available after infiltration, runoff, and evapotranspiration are budgeted, would be very similar to that of hurricane and tropical storm rainfall. Although runoff may increase during heavy storms, the rainfall rates which normally accompany a hurricane or tropical storm rarely exceed those from other sources, and when extremely high rainfall occurs it is usually limited to a relatively small part of the Water Management District. Runoff from

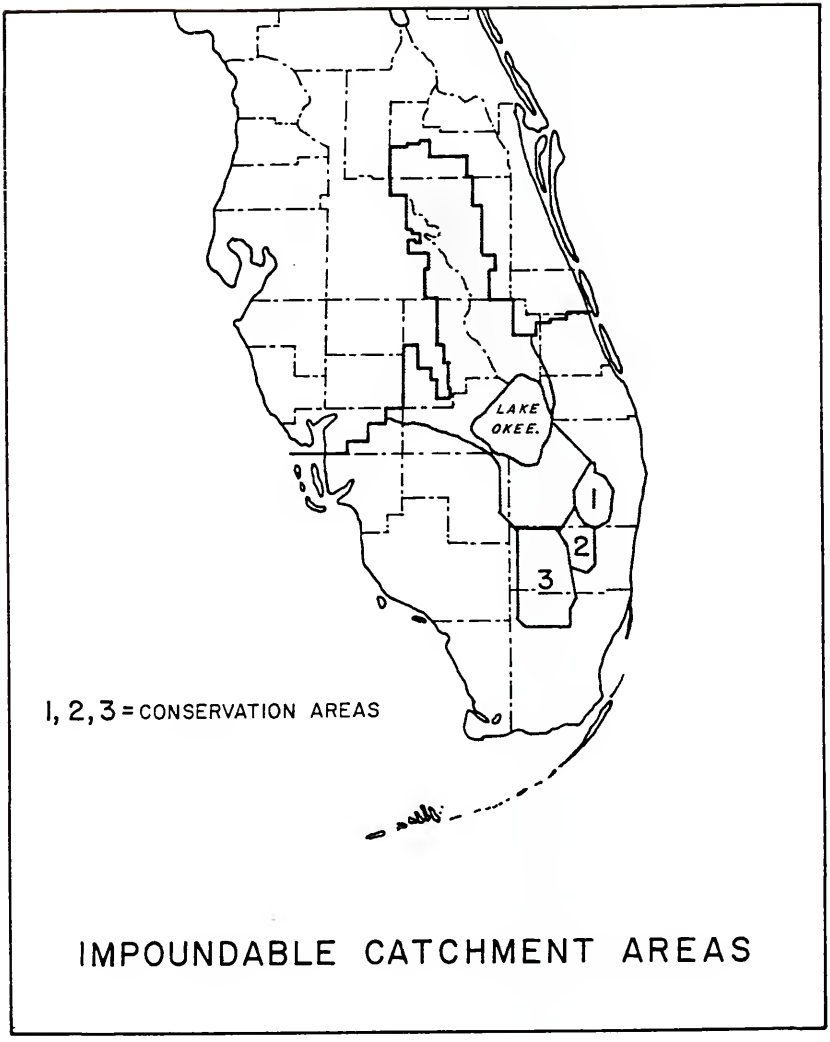

FIGURE 9

IMPOUNDABLE CATCHMENT AREAS

hurricanes and tropical storms may occasionally exceed runoff from other rainfall sources, but lighter rains often fail to provide significant soakage and may make no net contribution to terrestrial moisture after a day of evapotranspiration. Tropical cyclone rainfall is generally enough to add significant quantities of water to ground and surface storage.

CHAPTER 7

WATER SUPPLIES IN THE SOUTH FLORIDA WATER MANAGEMENT DISTRICT

The foregoing summaries and analyses of hurricane and tropical storm rainfall data provide information regarding the relative importance of rainfall from these sources as part of the total rainfall of the South Florida Water Management District and indicate the amount of usable water which remains after runoff and evapotranspiration have taken place. The use and management of water must also be considered, however, if the full significance of tropical cyclone rainfall to water supplies is to be understood. In the remainder of this study, the effects of reduced rainfall on water supplies are treated in relation to projected demands for water and the impacts that possibly declining supplies and increasing demands would have on water management policies and practices in the SFWMD.

Origin of the SFWMD

Attempts to influence the water balance in South Florida began in the 1850's, when the United States Congress put all swamp and overflow lands into state ownership through the Swamp Lands Act of 1850. Efforts to drain

wetlands were financed by the sale of land to private interests, and in Florida, a board of internal improvements was established in 1851 to negotiate these transactions. Draining wetlands continued to be the primary form of water management in the region until the 1930's. The U.S. Army Corps of Engineers entered the region in 1899 and began to construct numerous water control and diversion structures which are still used by the Corps and the South Florida Water Management District (Smith, 1980).

The hurricanes of 1926 and 1928 demonstrated that while existing canals were capable of handling routine drainage, they could not absorb the excess water from a severe storm rapidly enough to prevent flooding, and flood control thus became a new objective of water management in the region. In 1948, Congress adopted the Central and Southern Florida Flood Control Project and the following year, the Florida Legislature created the Central and Southern Florida Flood Control District. The Army Corps of Engineers assisted the Flood Control District by constructing and operating water control structures (Smith, 1980).

Extended drought between 1931 and 1945 brought the problem of maintaining adequate water supplies to the foreground. Groundwater levels became so low that saltwater intruded into municipal wells of coastal cities. Land which was normally underwater became dry and thousands of acres of "muck" soil were lost to fires (Smith, 1980).

Continued increases in water demand and worsening problems concerning supply culminated in the Florida Water Resources Act of 1972 which created the South Florida Water Management District as part of a statewide system of water management districts. Several modifications were made to water management district boundaries in South Florida by amendments in 1973 and 1976, leading to the present configuration of districts. Duties and authority of the water management districts were altered and clarified as part of the Environmental Reorganization Act of 1975.

The Water Resources Act states that the water management districts may be authorized to perform the following functions: 1) Administer and enforce all provisions of the Act, including the permitting of consumptive uses, regulation of wells, and management and storage of surface waters. 2) Cooperate with the federal government in matters of flood control, reclamation, and conservation. 3) Establish and control the level of water in canals, lakes, rivers, channels, reservoirs, and streams, and maintain those levels by means of dams, locks, flood gates, dikes, and other structures. 4) Plan, construct, operate, and maintain physical works.

Water Management Goals in the SFWMD

The South Florida Water Management District has published the set of objectives listed below.

1. Water Supply. Ensuring fresh water resources for all needs.

2. Water Conservation. To fully conserve and control the water resources in the District so as to realize their full beneficial use.

3. Prevention of Salt Water Intrusion. To protect fresh water through regulation of water use and by installing salinity control structures to hold fresh water levels high near the coast.

4. Flood Control. To prevent damage and control the discharge of water from floods in the event of hurricanes or excessive rainfall.

5. Protection and Enhancement of Fish and Wildlife. Conservation of our natural resources to prevent exploitation, destruction, or neglect.

6. Maintenance of Desirable Groundwater Levels. Providing canals, levees, dams, reservoirs, holding basins, pumping stations, and other works, for utillzation and conservation of surface and groundwater.

7. Navigation. To assist in maintaining the navigability of rivers and harbors.

8. Public Recreation. To operate and maintain quality water-based recreation facilities.

9. Preservation of Important Wilderness Areas and their Ecosystems. To ensure water managemnt practices are sensitive to environmentally fragile areas.

10. To Promote the Health, Safety, and General Welfare of the People of the State. (SFWMD, 1980, p. 5)

Practices which lead to the achievement of some of these goals may be detrimental to the accomplishment of others. For example, flood control is best achieved by keeping water levels in lakes, canals, and the ground low, while maintenance of water supplies is best served by keeping these same reservoirs at high levels. Accurate assessment of the amount of water in each phase of the hydrologic cycle, including rain that may come from tropical cyclones, is needed to achieve these objectives. Without a better understanding of tropical cyclone rainfall, water administrators could make more errors of the type committed in 1979 when they lowered canal levels enough to accommodate 12 inches of rain from Hurricane "David" (SFWMD, 1979) and only 2 inches materialized.

Present and Projected Water Demand in the SFWMD

Leach (1978a, 1978b) has tabulated the volume of water taken from various sources and applied to several major use categories for 1975. Pride (1973, 1975) has supplied similar information for 1965 and 1970, and Healy (1972) has provided data concerning the public water supplies of specific municipalities for 1970. Khanal (1976) and Toomey & Woelcke (1979) have used computer models to analyze water demands per capita for municipal supplies in the South Florida Water Management District. These data and models may be used along with census information to develop

projections of future water demands for the Water Management District or individual counties and municipalities within the District.

Information from the above sources and population figures from the United States censuses for 1960, 1970, and 1980 were used to project water demand at ten-year intervals through the year 2030 (Table 38). The amount of water consumed during each listed year is compared to the amount of water added to the supply by rainfall from all sources (Table 39). Water supply rates are based on rainfall from 1919 through 1948 and 1949 through 1978 so that the effects of reduced rainfall during the later interval could be observed. Supplies used are the net of annual groundwater infiltration and potential surface storage in impoundment areas, after one year of evapotranspiration. This formula assumes that all rain which falls in an impoundable area can be caught and saved, and should yield a generous estimate of supply.

The analysis of rainfall, earlier in this study, showed that during the interval from 1949 through 1978, mean annual rainfall was significantly lower than for the preceding thirty years, and that the difference in total rainfall corresponds approximately to the difference in rain from hurricanes for the two intervals. Thus, rainfall for the later interval may be used as a guide to the amount of moisture that would be available in ground and surface reservoirs if hurricanes failed to influence Florida,

TABLE 38

ANNUAL FRESH WATER DEMAND

(ACRE FEET)

YEAR	POPULATION SERVED	WITHDRAWN TOTAL	WITHDRAWN PER CAP	CONSUMED TOTAL	CONSUMED PER CAP
1965	2,200,000	3,404,224	1.549	1,556,214	.707
1970	2,709,000	2,364,726	.873	1,049,338	.387
1975	3,300,000	3,349,459	1.015	1,357,321	.411
PROJECTIONS ASSUMING 1965 WITHDRAWAL AND CONSUMPTION RATES					
1990	5,400,000	8,364,000	1.549	3,817,000	.707
2000	7,200,000	11,152,800	1.549	5,090,400	.707
2010	9,300,000	14,405,700	1.549	6,575,100	.707
2020	11,700,000	18,123,300	1.549	8,271,900	.707
2030	14,400,000	22,305,600	1.549	10,180,800	.707
PROJECTIONS ASSUMING 1970 WITHDRAWAL AND CONSUMPTION RATES					
1990	5,400,000	4,714,200	.873	2,069,800	.387
2000	7,200,000	6,285,600	.873	2,786,400	.387
2010	9,300,000	8,116,900	.873	3,599,100	.387
2020	11,700,000	10,214,100	.873	4,527,900	.387
2030	14,400,000	12,571,200	.873	5,572,800	.387
PROJECTIONS ASSUMING 1975 WITHDRAWAL AND CONSUMPTION RATES					
1990	5,400,000	5,481,000	1.015	2,219,400	.411
2000	7,200,000	7,308,000	1.015	2,959,200	.411
2010	9,300,000	9,439,500	1.015	3,822,300	.411
2020	11,700,000	11,875,500	1.015	4,808,700	.411
2030	14,400,000	14,616,000	1.015	5,918,400	.411

TABLE 39

NET BALANCE BETWEEN CONSUMPTION AND SUPPLY

(ACRE FEET)

YEAR	CONSUMED	SUPPLY-A[a]	BALANCE-A	SUPPLY-B[b]	BALANCE-B
1965	1,556,200	2,102,550	546,349	1,996,940	440,738
1970	1,049,300	2,102,550	1,053,250	1,996,940	947,638
1975	1,357,300	2,102,550	745,249	1,996,940	639,638
PROJECTIONS ASSUMING 1965 CONSUMPTION RATES					
1990	3,817,000	2,102,550	-1,714,450	1,996,940	-1,820,060
2000	5,090,400	2,102,550	-2,987,850	1,996,940	-3,093,460
2010	6,575,100	2,102,550	-4,472,550	1,996,940	-4,578,160
2020	8,271,900	2,102,550	-6,169,350	1,996,940	-6,274,960
2030	10,180,800	2,102,550	-8,078,250	1,996,940	-8,183,860
PROJECTIONS ASSUMING 1970 CONSUMPTION RATES					
1990	2,089,800	2,102,550	12,749	1,996,940	-92,862
2000	2,786,400	2,102,550	-683,852	1,996,940	-789,462
2010	3,599,100	2,102,550	-1,496,550	1,996,940	-1,602,160
2020	4,527,900	2,102,550	-2,425,350	1,996,940	-2,530,960
2030	5,572,800	2,102,550	-3,470,250	1,996,940	-3,575,860
PROJECTIONS ASSUMING 1975 CONSUMPTION RATES					
1990	2,219,400	2,102,550	-116,852	1,996,940	-222,462
2000	2,959,200	2,102,550	-856,652	1,996,940	-962,262
2010	3,822,300	2,102,550	-1,719,750	1,996,940	-1,825,360
2020	4,808,700	2,102,550	-2,706,150	1,996,940	-2,811,760
2030	5,918,400	2,102,550	-3,815,850	1,996,940	-3,921,460

a. SUPPLY-A and BALANCE-A are based on rainfall for 1919 through 1948
b. SUPPLY-B and BALANCE-B are based on rainfall for 1949 through 1978

no matter whether natural climatic change or weather modification was the cause. No consideration is given here to rainfall from tropical storms because the number of tropical storms and the amount of rainfall from them has continued undiminished through both thirty-year intervals and it is unlikely that storms of less than hurricane intensity would be seeded.

The population projections (Table 38) assume continued rapid growth at a rate which increases numerically with each interval but comprises a smaller percentage of the population than the increase of the previous interval. Census data show that population in the SFWMD increased by about 900,000 between 1960 and 1970, and by about 1,200,000 between 1970 and 1980. The difference between these two intervals is used to project the rate of increase for future ten-year intervals. Thus the increase in population from 1980 to 1990 is estimated at 1,500,000 and the increase for 1990 to 2000 is 1,800,000 and grows larger by 300,000 for each succeeding ten-year interval.

Historic water consumption rates do not show a continuous trend as does population growth. Total and per capita freshwater use increased continuously from the earliest found estimates (Leach, 1978b) through 1965, but then declined sharply so that the total volume in 1970 was only about two-thirds of what it had been in 1965, and per capita withdrawal and consumption were slightly above half of the 1965 rate. From 1970 to 1975, total water withdrawn

and consumed rose again to almost 1965 levels, but per capita use remained relatively low. Because of these fluctuations in the rates of water withdrawal and consumption, no clear rationale could be found for projecting increasing or decreasing rates into the future: therefore, estimates of consumption (Tables 38 and 39) are based on all three given rates.

Use of fresh water reached a peak during 1965 because of a very large quantity used for irrigation and the relatively high percentage of irrigation water which is consumed in use. Between 1965 and 1975 a decrease in the amount of water used for irrigation and a trend to adopt saline water for cooling thermal electricity generators relieved some of the demand for fresh water in the SFWMD (Leach, 1978b).

Significance of Water Supply and Demand Projections

The projections of water supply and use (Tables 38 and 39) indicate that the consumption rates of 1965 or 1975 would lead to demand exceeding the amount of new water available from rainfall by 1990 or sooner. Projections based on the lower 1970 rate of consumption show a small surplus of rainwater for 1990, but a deficit for each projected year thereafter using rainfall data for 1919 through 1948, and deficits for all projected years using rainfall data for 1949 through 1978.

The above projections consider only the mean annual rainfall and not its seasonal distribution or annual fluctuations. South Florida has a wet season in the summer alternating with a dry season each winter. Not all of the surplus rain that falls in an impoundable area during the wet season can be saved and much of what infiltrates the ground or is impounded in surface reservoirs is exposed to evapotranspiration for the greater part of a year. Relatively little excess water from a high rainfall year can be saved to serve the needs of a dry year and if the wet season falls to bring the normal amount of rain, a shortage of water, such as happened in 1971 (Benson & Gardner, 1974; Storch, 1974) may soon follow.

The geographical distribution of the water consumption also affects the ability of supply to meet demand. Although rainfall is spread across the entire Water Management District, water users are concentrated in coastal cities and a few inland agricultural areas. The South Florida Water Management District and the U.S. Army Corps of Engineers operate a complex system of canals and control structures in the southeastern part of the District to ration water from upstream areas to the coast, but the southwestern region of the Water Management District, where annual potential evapotranspiration exceeds rainfall, has no such system.

Another factor which affects the ability of a region to meet its water needs, is the relationship between the

quantity of water withdrawn and what is consumed. Less than half of the water withdrawn in the South Florida Water Management District is consumed in use (Table 38). Although the unconsumed water is returned to a ground or surface reservoir, it is necessary to have this water available for either direct use, as in thermal electric cooling, or so that a consumptive use, such as irrigation can take place. The amount of water withdrawn for any of the base years used exceeds the annual increment of new supply from rainfall. This is not a problem as long as enough water from past rainfall remains available, but if consumption exceeds new supplies by large amounts or for many years, the amount of water available for withdrawal could be reduced to levels that would restrict water usage even though enough water to match desired levels of consumption may remain.

When making projections, certain trends must be assumed to continue into the future. When the forecast future becomes the present, such trends are often found to change. Fluctuations in past water use rates illustrate the hazards of assuming any constant rate of water use in the future.

Events that are related to the issue of water consumption can be studied, however, so that some educated guesses can be made regarding future water use patterns. It is probably safe to assume that the per capita consumption of fresh water in the South Florida Water Management District should not be expected to rise sharply and may decline because of the increasing population which is

dependent upon a limited supply. Reduced per capita use rates are in fact essential to continued population growth in this area.

As population grows and public supplies require more water, the amount of water available for other uses will decline. Changes in the profile of water use patterns may cause a further decline in per capita consumption of fresh water. For example, water for irrigating orange groves will decline as urban development encroaches on agricultural land. Water which would formerly have been used to irrigate trees will be used directly by people instead.

CHAPTER 8

IMPLICATIONS OF REDUCED RAINFALL FOR WATER MANAGEMENT PLANNING

Water demand in the South Florida Water Management District will rise enough to consistently outstrip the region's present ability to meet dry season requirements within the next decade. If rainfall continues to be low, as it has been during recent years without hurricanes, persistent water shortages will arrive sooner than if rainfall returns to higher levels of the past, but regardless of which rainfall rate prevails, consumption of water in South Florida will soon exceed the amount of new water available from rainfall each year after evapotranspiration. Increasing demands placed upon a possibly declining supply will require that changes in water management policies and practices be adopted in order to make maximum use of available water.

General Implication for Water Management Policy

The policy of the SFWMD regarding storage of surplus water is to save all available water during the dry season and all the water that will fit in reservoirs up to

specified levels during the wet season (Kreitman, 1981). Since demand for water has already exceeded supply during dry years, any significant increase in demand will require comparable increases in storage so that more wet season rainfall can be saved for use during the dry season or for dry times during that part of the year which is usually wet. It would thus be wise for the SFWMD to adopt a policy of expanding its storage capacity.

The study of hurricane rainfall patterns shows that the South Florida Water Management District may be able to alter its policies concerning the acceptable water levels for storage areas without forfeiting flood control ability. When Hurricane "David" approached South Florida, water management officials based their estimates of how much rain to be prepared for on the amounts that fell in Haiti and Puerto Rico (SFWMD, 1979). "David" dropped 10 to 12 inches of rain on those mountainous islands, and advanced toward Florida in a much weakened state. Energy had dissipated from the storm because water needed to store latent heat had been removed and was not entirely replaced by the time "David" reached Florida. Even if "David" had made landfall at Miami and traveled across the center of the Water Management District, records of the rainfall brought by previous hurricanes indicate it is unlikely that the storm could have released more than 3 or 4 inches of rainfall over Florida's flat interior.

When rainfall as high as 10 to 12 inches occurs, it is usually found at only a few stations, while other stations may receive an inch or less. The maximum rainfall from any of the 85 hurricanes and tropical storms, which brought rain to South Florida between 1919 and 1978, averaged 7.86 inches for the nineteen stations used in this study, and the mean for all hurricanes and tropical storms for the 60-year study period is only 2.68 inches. Armed with the knowledge that tropical cyclones bring less rain than they had earlier believed, water management officials in South Florida might allow less margin of safety for flood prevention and make greater use of existing water storage capacity.

Implications for the Water Use and Supply Development Plan

The South Florida Water Management District has been formulating and modifying its Water Use and Supply Development Plan (SFWMD, 1978) since the District began to function. The first edition of most parts of the plan appeared in 1977 and these are scheduled for revision in 1981. A summary of the major recommendations of the plan appears below, followed by comments concerning implications that reduced rainfall or increased fresh water demand would have for each recommendation.

Conservation

Conservation may be used not only to decrease the demand for water but also to reduce the need for facilities to treat fresh water supplies and wastewater. It could also have ecological benefits by maintaining higher water levels in Lake Okeechobee and the three conservation areas. Recommendations of the plan concerning conservation are as follows:

> 1. Support and encourage conservation of water resources by suppliers, managers, the District, and all water users. Information and instruction on effective means for reducing water consumption should be provided to the above.
> 2. Educate the public on the impacts, advantages, and effectiveness of water conservation programs with respect to water resources, water supply, and wastewater treatment.
> 3. Require water conservation through efficient use provisions in consumptive and surface water management permits and during critical periods through implementation of appropriate Water Shortage Plans. (SFWMD, 1978, p. 5-1)

In a broad sense, the entire plan is concerned with conservation. Conservation is important in maintaining the usefulness of many resources, and is essential to the water supply of South Florida. Since demand for water in South Florida already exceeds supplies in dry years, the observed decline in rainfall and projected increases in demand indicate that water shortages should occur more frequently and last longer in the future. Strong and continuing emphasis on conservation could help alleviate these shortages and maintain the carrying capacity of the region.

Wellfield Development

Evaluation of wellfield development by SFWMD planners included estimating the water supply capability, or "safe yield" of the Biscayne and Palm Beach County shallow aquifers and determining the relationships between the number and size of wells and the balance of water in the aquifer. The main criterion used to develop safe sustained wellfield pumpage rates was the prevention of salt from intruding into existing coastal wellfields. The plan's recommendations state that the SFWMD should:

> 1. Encourage development of wellfields within the limits of safe aquifer yields in the Lower East Coast, as defined by the constraints of controlling saltwater intrusion to preserve existing wellfield uses, and minimizing adverse environmental impacts.
> 2. Provide local governments and utilities with assistance through District planning activities in selecting optimal wellfield locations.
> 3. Encourage regionalization of wellfields and associated facilities to reduce local costs, where applicable.
> 4. Encourage additional planning on a local level to assure timely development of wellfields. (SFWMD, 1978, p. 5-2)

Any future wellfield development must take into account that rainfall to recharge those wells may be less than long term means indicate. Analysis of rainfall data discloses not only that the second half of the study period was drier than the first half but also that the 1970's have been drier than any preceding decade studied. If this trend continues, curtailment of wellfield development should be considered. Osmotic intrusion of ocean salts is already

a problem along many parts of the coast, and continued wellfield development during a period of declining rainfall would accelerate this condition.

Backpumping

This set of recommendations concerns pumping water, that is now allowed to flow to the sea, back inland to be stored in the conservation areas. Backpumping can be used to aid flood control and water supply but may impair water quality by carrying salts from the coastal ends of canals many miles into the interior. The plan recommends continued study of this alternative in order to evaluate its effects on the environment, and specifies that the best available water quality should be maintained, as stated below.

> 1. Support and encourage the continuing evaluation of backpumping, while concurrently developing an optimized Conservation Area management program through water quantity and quality studies of the impact of backpumping in vegetation, fish and wildlife.
> 2. Local government planning and development approvals and SFWMD surface water management permitting should continue to require that the best available water quality and land management practices be implemented to maintain and improve water quality. (SFWMD, 1978, p. 5-5)

Beyond the observation that any means to conserve water without damaging the environment should be considered, the findings of the present study do not materially affect the recommendations of the SFWMD plan concerning backpumping. This practice may be useful during certain seasons regardless of long term rainfall rates.

Demineralization

Demineralization in South Florida refers primarily to desalinization of sea water or brackish coastal water from estuaries or wells. Demineralized water can be used to supplement fresh water supplies, or may be injected into shallow aquifers to impede intrusion of salt in coastal areas. The recommendations of the plan, given below, provide no definitive statement on this topic.

> 1. Support the use of demineralization on a local and/or individual user basis where cost and energy effective and proper disposal techniques are employed.
> 2. Implementation of regional demineralization facilities should be deferred until additional studies on cost and energy requirements are completed. (SFWMD, 1978, p. 5-7)

Although demineralization is a potential means for supplementing inadequate future water supplies, the cost of this alternative may preclude its use. The present study indicates that rainfall brings more than enough water to meet the needs of the SFWMD if it can be stored or used before it evaporates. As long as fresh water is available from inland sources, demineralizing sea water is not an attractive alternative. A reduction in the amount of rainfall from tropical cyclones, however, would probably have little impact on this proposal.

Deep Aquifer Storage

Deep aquifer storage is a means for expanding the volume of groundwater storage capacity. It involves

injection, storage, and retrieval of freshwater into saline portions of the Floridan Aquifer so that surplus water from rainy periods may be saved and recovered during times of draught. Official recommendations concerning this practice, stated below, are noncommittal, pending further research.

> 1. Continue research and development to define the potential and costs of this alternative.
> 2. Defer implementation of construction for other than research purposes until studies are complete. (SFWMD, 1978, p. 5-8)

Reservoir capacity is a major factor which limits the supply of fresh water in South Florida. Deep aquifer injection would not only increase water storage capacity, but would do so in places that would not suffer rapid depletion from evapotranspiration. If it proves to be feasible, this practice could become a valuable addition to the storage capacity needed to forestall impending water shortages.

Increased Lake Okeechobee Storage

Lake Okeechobee is the main surface storage reservoir in the SFWMD. The storage capacity of the lake can be substantially enlarged by allowing higher water levels to accumulate behind its dikes. The following statement appears in the plan regarding this alternative.

> 1. The increased regulation schedule of 15.5 to 17.5 ft. msl., which can be attained with existing facilities and is currently being considered by the Corps of Engineers, should be implemented as soon as possible.

2. Further increases in regulation schedule requiring additional construction should be deferred until:

a. Monitoring of the Lake's vegetation, fish and wildlife population has documented changes, if any, which may result from the new regulation schedule and increased future water requirements. This knowledge will provide the scientific basis to more accurately predict the environmental changes which could occur under higher regulation schedules and increased water supply releases from the Lake.

b. The cost-effectiveness of the capital expenditures for the structural facilities needed to attain higher regulation schedules has been demonstrated. (SFWMD, 1978, p. 5-3)

The recommended increase of two feet to the allowable water level in Lake Okeechobee has already been implemented. Additional increments of storage capacity of this magnitude will be needed in the future but large capital outlay and extensive revision of control works will be required for any further enlargement to the capacity of the Lake. Since Lake Okeechobee is one of the few possible places in the SFWMD to locate a large increase in surface storage, this alternative should be seriously considered. With present storage reservoirs already being used to capacity, the need for additional storage to meet growing demand is obvious.

Wastewater Reuse

Public response in the SFWMD has been in favor of the proposal of wastewater reuse for non-potable uses. Wastewater is a large potential source of fresh water and regionalization of water treatment plants, going on in some parts of the SFWMD, will result in having this water

available in large quantities at specific sites. The plan includes the following comments on this topic.

> 1. Support local governments and utilities that desire to investigate this alternative for specific areas.
> 2. Continue to assess the public support (which has been largely in favor of wastewater reuse for nonpotable uses) and supply capabilities of this alternative.
> 3. Defer implementation until future studies confirm or deny the viability of the alternative.
> 4. Support the Corps of Engineers study of this alternative as part of the South Florida Water Supply study. (SFWMD, 1978, p. 5-8)

Wastewater reuse might well have been listed under the heading of conservation. It is a basic means to achieve more efficient use and reduced withdrawal and to enhance limited water supplies regardless of a decline in hurricane rainfall.

Forward Pumping

Forward pumping requires the construction of new locks landward of existing salinity control structures and pumping water into the space in between from further inland. This should maintain high canal stages and high groundwater levels near the coast which would allow additional wellfield development and impede saltwater intrusion. This proposal is relatively recent, and no decision concerning it appears in the plan, which states simply that: "Any decisions on forward pumping must be deferred until a later date because additional data and analysis methods are necessary to properly evaluate this alternative" (SFWMD, 1978, p. 5-8).

If this practice proves to be practicable, it could be used to increase storage in the groundwater reservoir. A decreasing amount of water available, because of possible declining rainfall and increasing water use may, however, restrain the use of this technique.

Weather Modification

In this context, weather modification refers to cloud seeding to stimulate rain. The plan recommends against this practice because of "unresolved legal, social, political, and economic problems," and states that: "Because of the uncertainty of supply when it is needed and the many unresolved questions, any further investigation of this alternative by the District should be discontinued" (SFWMD, 1978, p. 5-9).

In the future, however, when chronic acute water shortages become common, it may be necessary to reconsider this alternative. The apparent problems associated with weather modification may become less significant as the need for water rises above the ability of natural rainfall to replenish supplies. If a hurricane suppression program becomes operable, additional weather modification may be required to compensate for lost hurricane rainfall.

Thin Films over Storage Areas

Thin films over storage areas are a means of suppressing evaporation. Unfortunately, these films are

very fragile and difficult to maintain and have generally failed to adequately perform their function, leading SFWMD planners to conclude that no further consideration should be given to this alternative.

The amount of water from rainfall in South Florida, with or without hurricanes, is far more than is needed to meet present demands, but most of it is lost to evaporation and transpiration. If evaporative losses from surface storage areas could be suppressed, South Florida would have an adequate water supply for many years to come. The SFWMD should reconsider the use of evaporation control techniques, including means other than surface films, and consider sponsoring research on this topic. A breakthrough in this area could solve many problems for South Florida and other water short regions.

Water Importation

Legal, social, political, and economic problems, similar to those affecting weather modification make importing water from outside the Water Management District impractical, so that the plan's recommendation for this proposal also is that no further consideration should be given to this alternative. Although South Florida will need more water in the future, this does not appear to be the way to acquire it. The findings of the present study, however, have no direct bearing on this matter.

Additional Water Conservation Areas

Recommendations concerning this topic are scheduled to appear in the revision of the Water Use and Supply Development Plan which should be published in the fall of 1981. The recommendations will depend on studies of cost, environmental effects, supply capability, and political implications. Significant new storage capacity could result from this action and it therefore requires serious consideration.

Reclamation and Systems Optimization

This area is also to be addressed in the next revision of the plan. This proposal calls for increasing available supplies by preventing waste and improving the operating efficiency of water control structures. Any such improvement in efficiency would help alleviate projected future water shortages and may be a valuable addition to the total water conservation effort.

Closing Comment

The Water Use and Supply Development Plan of the South Florida Water Management District focuses primarily upon means to maintain and increase supply, with relatively little attention given to reducing demand. Griggs (1979) has stated three basic methods for reducing the demand for water:

> . . . 1) limiting development which is reliant upon large quantities of water. 2) rationing or scheduling the use of existing supplies amongst present and future users, and 3) by increasing the efficiency of water use amongst consumers. (Griggs, 1979, p. 3)

The plan directly addresses only the last of these practices, although many of the plan's recommendations are also concerned with maintaining long term supply for the benefit of both present and future users. Legal restraints to land development and population increase are not discussed in the plan, and are beyond the authority of the Water Management District to impose. The permitting of consumptive uses of water are, however, within the authority of the Water Management Districts and can be used to limit development which relies on large quantities of water. The plan fails to treat this important topic.

CHAPTER 9

SUMMARY AND CONCLUSIONS

Hamrick (1972), a planning engineer for the South Florida Water Management District, has stated:

> Water may be transported for considerable distances from where it fell as rain, and it may be stored for long periods of time, but with very few exceptions it originates as rainfall. Consequently, the measurement and study of rainfall is in truth the measurement and study of our potential water supply. (Hamrick, 1972, p. 1)

This research has concerned itself with rainfall from hurricanes and tropical storms and the amount of water that such systems bring. The data which have been collected for nineteen weather stations in and near the South Florida Water Management District indicate that the mean annual rainfall from hurricanes for the district is 20.05 inches, or 3.8 percent of the annual total and that the mean rainfall from tropical storms is 1.74 inches or 3.2 percent of the annual rainfall. These quantities do not remain constant, however, and the annual rainfall from hurricanes during the second half of the study period is only 1.25 inches per year, significantly less than the 2.86 inches which came from hurricanes during the preceding thirty years.

Hurricanes and tropical storms add significant quantities of water to the environment of South Florida and although the amount of water remaining after evapotranspiration is relatively small, water supplies from all other sources are also depleted by evapotranspiration. The relative importance of water from tropical cyclones compared to the amount of water from other sources is similar to the relative amount of rainfall from tropical cyclones compared to that from other sources.

At times, however, rain from tropical cyclones may be more important than the given percentages would suggest. Mean annual precipitation exceeds potential evapotranspiration by no more than 14 inches in any part of the South Florida Water Management District and in some areas precipitation is less than potential evapotranspiration (Visher and Hughes, 1969). If two inches of rain were withdrawn from the annual total as a consequence of modifying hurricanes, at least one-seventh of the net annual increment of new water could be lost in the wettest areas, and in places where rainfall exceeds potential evaporation by less than two inches, a net annual surplus of moisture could become a net deficit. Hurricanes bring only 3.8 percent of the mean annual rainfall to the region, but if the total rainfall on a given year is close to the level of potential evapotranspiration for a certain place, then hurricane rainfall may account for a substantially greater proportion of the amount of available water.

The number of hurricanes bringing rain to South Florida in recent years has dropped sharply from what it had been during earlier times. Although the atmospheric mechanisms that cause this have not been identified, it remains a fact there is a decrease in total annual rainfall associated with the decline in hurricane numbers. This decrease, however, is not during the hurricane season, but is concentrated primarily during other times of the year which have always been relatively dry, thus magnifying its effects upon supply.

Projections of water supply and use indicate that demand may be expected to consistently exceed annually renewable supplies by 1990. These projections, however, consider only mean annual rainfall for the district and do not account for temporal variations or the geographical distribution of rainfall. Unusually long intervals of dry weather or a concentration of rain in areas where it cannot be saved for future use, can lead to water shortages in the region at any time. The entire Peninsula of Florida is at present, in fact, experiencing a drought which is contributing to water shortages in areas of high demand (Clary & Melton, 1981; "Drought . . . ," 1981; "Everglades . . . ," 1981; "Florida Gets Some Rain . . . ," 1981; "Florida's Spring Drought . . . ," 1981; Hartman, 1981; Jean, 1981; Klein, 1981; "Officials Say Drought . . . ," 1981; "Showers Little Help . . . ," 1981).

The study of hurricane rainfall patterns has shown that although significant quantities of water are brought by these storms, the rainfall from individual hurricanes tends to be less than what officials of the South Florida Water Management District had believed, and that the long term rainfall from hurricanes has been declining in recent years. These observations have significant implications for water management policies in the district. The responsibilities of the Water Management District include the intrinsic conflict of maintaining storage reservoirs at high enough levels to assure adequate water supplies while at the same time keeping levels low enough to prevent flooding. The information about rainfall contained in this research could be used to meet these conflicting goals more efficiently by providing more accurate information about the amount of rainfall that may be expected from a typical hurricane.

The differences between estimated water supplies, based on the first thirty years of the study period compared with supplies based on the second thirty years are significant but minor when contrasted to the rapidly increasing demand for water that is projected during the next fifty years. This indicates the importance of human influence on the hydrologic cycle. The lowering of South Florida's freshwater table has been more affected by human influence than it has by climatic change in the past (Thomas, 1974) and that influence will become more pronounced in the future. As human impact on the hydrologic cycle becomes

greater, the need for effective water management increases. As population and the demand for water grow, water management policies must be continually re-evaluated and new means to enhance supply must be considered.

Past human influence on the hydrologic cycle in South Florida has been mainly through withdrawal and consumption of water from ground and surface sources. In the future, atmospheric moisture may be influenced as well, by seeding cumulus clouds to initiate rainfall or by modifying hurricanes and reducing the amount of rain which falls over land. The full consequences of these actions are difficult to fathom. Continued study of such topics as discussed in the Water Use and Supply Development Plan, is needed to evaluate more fully the effects of human influence on water in the South Florida Water Management District and in many other regions where mankind's numbers make significant changes to the water budget.

APPENDIX A
HURRICANE RAINFALL PER STORM

CITY	SEPT. 9-10 1919	SEPT. 25-30 1920	OCT. 24-25 1921	OCT. 19-21 1924	JULY 26-28 1926	OCT. 20-21 1926	AUG. 7- 9 1928	SEPT. 16-17 1928	SEPT. 27-29 1929	JL-AU 29- 1 1933	SEPT. 1 1933
ARCADIA	1.97	0.59	4.60*	4.60	0.04	0.05	4.28	1.22	3.04	2.50	0.00
AVON PARK	0.55	1.22	5.27	3.31	1.35	0.13	5.29	3.13	3.26	2.18	0.10
BARTOW	0.05	1.50	5.55	2.62	1.51	0.00	3.92	3.25	1.99	0.23	0.00
BELLE GLADE	0.86*	1.87*	1.84*	6.86	1.27	2.62	4.62	4.78*	5.19	3.34	0.70
EVERGLADES CITY	0.56*	2.06*	2.09*	7.88*	0.50*	2.92*	3.65	2.37*	9.37**	2.00	0.00
FELLSMERE	0.28	0.53	2.16	5.51	6.88	0.20	6.75*	5.20	1.50	3.43	0.11
FORT LAUDERDALE	3.10	1.09	1.91	18.24	1.23	5.75	6.03	6.30	5.75	4.19	0.08
FORT MYERS	0.10	0.86	3.92	15.66	0.07	0.10	2.70	0.92	6.67	1.44	0.18
FORT PIERCE	0.97	1.65	2.27	5.48	5.12	0.30	8.21	5.20*	0.28	6.86*	0.06
HOMESTEAD	1.41	3.25	0.25	0.09	0.93*	5.73*	2.21	3.82	4.50	1.35	0.17
ISLEWORTH	0.00	1.59	3.09*	0.76	4.34	0.12	8.32	2.02	0.26	0.00	0.00
KISSIMMEE	0.00*	3.68	3.09*	1.47	3.45*	0.07*	5.49	0.01	0.12	0.51	0.00
LA BELLE	0.58*	0.72*	2.43*	12.40*	0.32*	0.21*	3.07*	2.09*	7.77	5.26	0.10
MIAMI	0.38	1.30	0.46	1.64	0.93	5.73	1.65	9.27	11.96	0.75	0.02
MOORE HAVEN	0.96	0.60	1.66	6.26	0.56	0.21*	3.44	3.26	3.67	3.41	0.01
OKEECHOBEE	0.79	0.30	0.90	8.15	2.04	0.32	5.83*	4.23*	3.30	7.80	0.00
ORLANDO	0.00	5.29	6.17	0.78	2.42	0.02	5.15	2.12	0.37	0.11	0.00
PUNTA GORDA	0.92	0.53	4.60*	9.48*	0.09	0.10	2.41	0.81	3.63	3.61	0.01
WEST PALM BEACH	0.75	3.14	2.01	10.68	1.47	2.00	6.19	6.30*	1.57	15.76	0.27

* MISSING DATA, VALUES SHOWN ARE INTERPOLATED FROM 2 OR 3 NEARBY STATIONS.
** INCLUDES 2 OR MORE DAYS OF CUMULATIVE RAINFALL IN ORIGINAL CLIMATOLOGICAL DATA.

APPENDIX A (CONTINUED)
HURRICANE RAINFALL PER STORM

CITY	SEPT. 4- 6 1933	OCT. 3- 5 1933	SEPT. 2- 5 1935	SEPT. 28-29 1935	NOV. 4- 5 1935	JULY 29-30 1936	AUG. 11-13 1939	OCT. 6 1941	OCT. 16-19 1944	JUNE 21-24 1945	SEPT. 14-16 1945
ARCADIA	5.01	0.61	7.50	0.25	0.04	0.30	2.13	0.10	2.56	8.25	2.44
AVON PARK	9.90	0.62	3.93	0.02	0.14	0.00	5.07	0.09	4.29	9.80	4.23
BARTOW	14.25	0.34	4.58	0.04	0.15	0.88	2.51	0.00	5.40	11.00	3.08
BELLE GLADE	7.17	0.62	5.14	0.31	0.23	0.90	1.19	0.07	6.20	6.70	5.91
EVERGLADES CITY	1.84	3.66	13.76	0.46	0.14	2.32	2.54	5.50	4.86	2.25	4.65
FELLSMERE	6.52	2.21	2.67	1.18	0.10	0.68	2.03	0.09	9.03	6.83	5.66
FORT LAUDERDALE	2.07	6.58	2.52	0.74	1.82	1.56	0.75	0.00	5.05*	2.14	2.79*
FORT MYERS	1.53	0.41	9.90	0.03	0.07	2.38	0.28	0.19	5.56	7.93	1.95
FORT PIERCE	5.57**	1.49	1.52	0.40	0.18	0.30	1.46	0.01	9.55	3.06	4.05
HOMESTEAD	0.29	13.29	11.15	0.94	5.35	2.38	0.22	0.62	2.15	1.96	5.90
ISLEWORTH	10.01	0.77	1.61	0.00	0.18	0.79	1.38	0.00	8.11	8.38	7.11
KISSIMMEE	12.36	0.95	3.40	0.25	0.04	0.00	1.64	0.00	7.83	11.02	6.04
LA BELLE	1.78	0.41	6.58	0.34	0.10	1.02	0.91	0.11	3.95	4.60	4.96
MIAMI	1.54	9.31	3.75	0.84	4.20	1.16	0.19	0.35	0.87	1.33	1.93
MOORE HAVEN	2.51	1.33	4.46	0.32	0.24	0.20	1.96	0.02	2.88	4.01	4.57
OKEECHOBEE	8.00	1.41*	2.90	0.65	0.38	0.93	3.69**	0.00	6.22*	3.53*	3.85
ORLANDO	12.06	1.42	1.50	0.05	0.34	0.16	1.15	0.21	8.12	8.89	11.11
PUNTA GORDA	3.25	0.24	13.25	0.01	0.05	2.25	1.68	0.05	3.40	10.26	0.94
WEST PALM BEACH	9.84	3.14	2.11	0.95	0.33	0.13	2.51	0.04	5.59	12.18	3.64

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APPENDIX A (CONTINUED)
HURRICANE RAINFALL PER STORM

CITY	OCT. 7- 8 1946	SEPT. 17-18 1947	OCT. 11-12 1947	SEPT. 21-23 1948	OCT. 4- 5 1948	AUG. 26-28 1949	SEPT. 3- 6 1950	OCT. 15-18 1950	MAY 17 1951	OCT. 16-19 1959	SEPT. 9-11 1960
ARCADIA	0.55	3.37	0.32	4.88**	1.05	5.84	5.78	2.54	0.50	1.46	6.68
AVON PARK	1.46	5.07	0.53	7.25	0.80	9.28	2.93	5.33	0.03	3.09	7.13
BARTOW	1.85	6.71	0.03	5.93	1.07	4.93	4.82	4.58	0.06	2.95	7.65**
BELLE GLADE	0.87	7.30	4.49	8.96	1.84**	8.23	1.95	7.56	0.12	4.55	4.63
EVERGLADES CITY	0.72	3.84	6.70	8.65	3.40	1.10	3.24	1.04	0.07	4.23	6.40*
FELLSMERE	2.32	6.32	1.03	7.33	2.56	5.59	2.26	11.98	0.09	3.42	2.25**
FORT LAUDERDALE	1.50	2.90	13.10	9.00	11.00	4.00	1.75	4.07	0.00	2.80	5.90
FORT MYERS	0.98	8.72	0.97	8.37	2.71	0.98	4.52	0.98	0.02	7.83	4.84
FORT PIERCE	1.63	6.79	2.95	6.48	0.95**	4.17**	5.07	7.64	0.00	5.98	1.72
HOMESTEAD	2.50	1.28	9.71	7.82	9.56	1.33	1.79	2.98	0.79	2.05	7.79
ISLEWORTH	1.85	3.28	0.09	4.15	1.70	4.37	8.04	9.85	0.00	0.76	6.95
KISSIMMEE	2.34	5.85	0.27	6.74	1.41	5.43	6.68	8.46	0.20	1.55	6.55
LA BELLE	0.77	10.40**	1.46	7.25**	2.30	1.85	2.56	2.23	0.00	4.60	3.91
MIAMI	0.40	3.49	5.04	2.89	6.30	2.03	1.07	5.58	0.19	3.06	8.48
MOORE HAVEN	1.08	5.67	2.45	10.26	2.03	4.80	2.68	3.29	0.00	5.78	4.43
OKEECHOBEE	1.32	4.10	2.18	5.94	1.51**	7.38	1.57	5.65	0.00	2.30	0.75
ORLANDO	2.73	3.14	0.18	6.91	0.86	5.66	6.28	14.19	0.06	1.15	2.88
PUNTA GORDA	1.10	7.93	1.11	3.30**	2.53	3.31	7.64	2.80	0.00	4.40	7.40**
WEST PALM BEACH	2.23	4.76	0.00	7.57	7.34	5.87*	2.48	7.82	0.17	3.35	1.34

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APPENDIX A (CONTINUED)
HURRICANE RAINFALL PER STORM

CITY	AUG. 26-28 1964	SEPT. 9-11 1964	SP-OC 27- 6 1964	OCT. 14-15 1964	SEPT. 7- 9 1965	JUNE 8- 9 1966	OCT. 2- 5 1966	OCT. 16-19 1968
ARCADIA	1.20*	0.80*	0.23*	0.01*	1.16	2.48**	0.16	4.64
AVON PARK	1.64	1.29	0.26	0.01	1.96	3.07	0.23	2.08
BARTOW	0.59	1.63	0.35	0.08	0.96	2.63	0.41	1.72
BELLE GLADE	1.69	0.08	0.47	5.10	2.10	2.01	0.42	3.83
EVERGLADES CITY	0.05	0.00	0.69	3.22	2.91	2.48	1.12	3.18
FELLSMERE	4.95	0.55	1.08	0.00	1.17*	3.51*	0.56	0.95
FORT LAUDERDALE	5.62	0.00	1.03	1.95	3.76	7.61	3.42	3.48
FORT MYERS	0.62	0.51	0.78	0.02	0.42	2.36	0.18	4.50
FORT PIERCE	5.96	0.66	0.39	0.88	1.06	3.80	0.69	2.65
HOMESTEAD	1.26	0.27	0.65	2.02	5.59	7.46	1.35	5.19
ISLEWORTH	0.81	4.96	0.25	0.38	0.29	5.56	0.71	3.31
KISSIMMEE	0.55	5.48	0.27	0.38	0.08	2.29	0.47	1.92
LA BELLE	0.76	0.00	0.20	0.00	1.19	2.44	0.69	3.58
MIAMI	6.94	0.10	0.19	1.70	6.03	7.70	3.18	3.88
MOORE HAVEN	0.68	0.00	0.47	0.51	2.04	3.12	1.34	2.38
OKEECHOBEE	4.55	0.59	0.96	0.43	1.28	3.21	0.72	1.93
ORLANDO	0.29	5.99	0.29	0.38	0.27	2.26	0.09	3.61
PUNTA GORDA	0.69	0.30	0.49	0.01*	0.78	2.42*	0.29	2.29
WEST PALM BEACH	4.40	0.06	0.47	2.38	0.65	5.18	0.68	3.73

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APPENDIX B
TROPICAL STORM RAINFALL PER STORM

CITY	NV-DC 30- 1 1925	SEPT. 15-17 1926	AUG. 12-14 1928	SEPT. 8-10 1930	AUG. 29-31 1932	MAY 26-28 1934	JULY 22-23 1934	JUNE 13-15 1936	AUG. 21-22 1936	JULY 28-30 1937	AUG. 29-31 1937
ARCADIA	2.00	3.33	3.70	1.21	2.33	0.72	0.66	2.01	0.21	1.05	2.38
AVON PARK	2.65	5.77	1.60	3.90	0.18	1.28	0.09	1.21*	0.76	0.24	1.58
BARTOW	2.97	5.29	2.78	2.78	1.38	2.90	1.42	0.40	0.26	1.38	1.06
BELLE GLADE	0.82	7.63**	2.59	0.74	2.22	1.01	0.78	7.93	0.04	1.93	1.33
EVERGLADES CITY	5.47*	8.94*	5.29	0.74	9.68	0.39	1.06	18.75	0.60	1.94	0.66
FELLSMERE	4.17	7.47	4.54	5.51	1.58	4.25	0.10	2.58	2.57	2.11	1.04
FORT LAUDERDALE	6.23	10.06*	2.84	1.46	4.61	0.36	0.18	9.67	0.73	0.64	2.02
FORT MYERS	4.70	8.04	4.21	5.82	8.13	1.32	0.66	10.53	0.09	0.50	0.93
FORT PIERCE	7.12	7.08	1.98	2.91	1.60	0.71	0.22	2.65	0.18	0.76	0.68
HOMESTEAD	6.23*	9.85*	4.44	1.51	5.19	0.60	0.36	6.00	3.29	0.11	1.18
ISLEWORTH	2.25	1.71	0.65	0.82	0.81	0.82	2.66	2.41	1.67	2.84	3.73
KISSIMMEE	3.31*	2.81*	0.86	0.10	1.05	1.95	2.76	1.55	0.58	1.96	2.83
LA BELLE	2.76*	6.00*	3.67*	6.60	4.95	4.05	0.50	13.52	0.18	0.00	0.41
MIAMI	6.23*	9.85	3.30	1.74	10.33	3.02	1.37	7.43	1.07	1.17	0.13
MOORE HAVEN	0.81	6.00*	3.12	4.78	3.18	2.64	1.60	2.12	0.44	1.87	0.77
OKEECHOBEE	1.90	4.06	0.00	2.60	4.58	3.52	0.59	4.50	0.61	0.07	1.70
ORLANDO	4.37	5.28	2.26	0.34	0.28	0.98	2.25	4.41	2.62	1.69	3.09
PUNTA GORDA	2.43	8.10	8.28	3.04	4.24	0.87	0.61	3.48	0.73	2.13	1.83
WEST PALM BEACH	1.27	6.82	0.73	3.01	4.44	2.83	0.02	9.41	1.35	0.36	0.69

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APPENDIX B (CONTINUED)
TROPICAL STORM RAINFALL PER STORM

CITY	OCT. 13-17 1938	AUG. 2- 3 1940	SEPT. 15-17 1941	OCT. 17-21 1941	SEPT. 3- 5 1945	NOV. 1- 2 1946	AUG. 19-20 1947	SEPT. 22-23 1947	OCT. 5- 6 1947	OCT. 1- 3 1951	FEB. 2- 3 1952
ARCADIA	4.66	1.05	1.47	1.75	2.80	0.24	0.09	1.95	0.64	5.89	1.14
AVON PARK	5.76	0.10	0.52	1.94	1.82	0.55	0.37	2.49	0.35	3.30	1.11
BARTOW	6.32	1.31	0.65	0.72	1.36	0.50	0.77	3.30	1.16	0.81	0.77
BELLE GLADE	1.46	0.97	3.35	1.73	2.04	6.95	2.26	2.05	0.99	2.21	2.67
EVERGLADES CITY	2.97	0.00	0.65	1.56	5.33	1.65	0.73	4.32	0.85	1.43	3.67
FELLSMERE	2.11	0.00	0.37	8.94	2.13	1.47	0.63	6.92	1.70	1.80	1.90
FORT LAUDERDALE	0.50	1.64	0.89	3.66	4.52*	1.01	2.10	1.40	0.90	3.35	1.30
FORT MYERS	2.73	4.04	0.51	0.18	1.76	2.23	0.29	3.11	0.08	10.94	1.95
FORT PIERCE	3.86	2.01	5.20	3.40	5.00	2.30	2.21	3.66	4.66	6.06	3.04
HOMESTEAD	1.55	1.05	4.72	2.20	1.98	1.39	4.40	1.93	0.19	2.94	1.52
ISLEWORTH	2.70	0.44	1.62	2.36	2.84	0.52	1.13	1.39	0.16	1.40**	0.59
KISSIMMEE	3.43	2.03	1.54	2.61	1.12	0.65	0.24	1.25	0.27	1.99	0.66
LA BELLE	4.00	1.30	0.91	0.54	1.94	1.70**	0.82*	2.90*	0.20	10.08**	1.43
MIAMI	1.37	0.23	0.66	0.71	2.75	1.17	0.88	0.56	1.95	3.98	0.80
MOORE HAVEN	3.61	0.83	1.50	2.66	1.35	2.12	1.35	2.68	1.96	7.22	2.46
OKEECHOBEE	3.97	0.60	0.66	5.30	1.00	1.46	0.05	1.30	0.70	9.83	1.62
ORLANDO	2.82	0.93	1.97	3.43	0.51	0.50	1.08	2.65	0.16	2.02	0.68
PUNTA GORDA	3.00	2.51	2.88	0.92	2.20	0.92	0.10	2.04	0.00	9.84	1.51
WEST PALM BEACH	0.52	1.80	2.37	1.18	6.28	2.54	1.01	2.17	0.56	4.60	1.19

* MISSING DATA, VALUES SHOWN ARE INTERPOLATED FROM 2 OR 3 NEARBY STATIONS.
** INCLUDES 2 OR MORE DAYS OF CUMULATIVE RAINFALL IN ORIGINAL CLIMATOLOGICAL DATA.

APPENDIX B (CONTINUED)
TROPICAL STORM RAINFALL PER STORM

CITY	AUG. 27-31 1953	OCT. 3- 5 1953	OCT. 7-10 1953	JUNE 16-20 1959	SEPT. 21-25 1960	AUG. 24-26 1962	JUNE 5- 6 1964	SEPT. 7- 8 1967	JUNE 2- 6 1968	JUNE 17-20 1968	AUG. 9-10 1968
ARCADIA	1.44	0.19	8.44	1.34	0.67	0.59	1.03*	0.00	8.05	1.61	0.02
AVON PARK	2.93	0.64	4.18	7.35	3.01	0.37	0.73	0.00	7.98	0.81	0.00
BARTOW	1.92	0.10	2.03	6.18	1.62	0.51	0.01	0.00	5.18	1.45	0.04
BELLE GLADE	11.54	0.61	5.50	7.52	3.74	0.39	1.17	0.03	3.82	1.57	0.40
EVERGLADES CITY	2.96	0.15	2.03	10.61	3.25*	0.97	3.20	0.00	5.56	1.48	0.01
FELLSMERE	8.74	3.19	5.58	7.98	15.26	1.91	1.94	0.22*	5.42	1.33	2.10
FORT LAUDERDALE	6.35	3.25	3.60	7.50	6.77	0.27	1.50	0.10	4.65	2.69	2.11
FORT MYERS	1.27	0.43	5.02	13.59	1.36	1.77	1.15	0.00	6.22	3.41	0.90
FORT PIERCE	1.29	0.98	3.95	9.12	9.75	0.18	0.58	0.44	7.16	1.86	1.69
HOMESTEAD	1.14	1.69	3.64	6.61	5.13	0.09	2.78	0.00	3.27	6.11	1.36
ISLEWORTH	2.38	0.49	1.19	4.08	1.52	1.16	2.93	0.39	7.39	1.35	0.00
KISSIMMEE	3.15	0.78	1.95	6.88	3.19	1.52*	2.64*	0.70	8.83	1.39	0.00
LA BELLE	4.29	0.75	4.03	8.42	0.93	0.52	2.49	0.00	3.79	1.74	0.46
MIAMI	4.22	2.44	3.79	12.29	7.47	0.18	5.18	0.01	4.28	4.34	1.69
MOORE HAVEN	2.89	0.23	6.27	7.03	1.71	0.52	2.87	0.01	4.22	1.23	0.02
OKEECHOBEE	3.98	1.44	3.58	8.30	4.03	2.84	0.42	0.00	5.66	1.34	0.20
ORLANDO	3.58	1.74	0.70	5.52	1.07	1.87	2.35	1.18	10.63	4.43	0.13
PUNTA GORDA	1.70	0.02	7.06	8.19	3.04	0.81	1.32	0.00	6.11	3.14	0.05
WEST PALM BEACH	4.28	3.43	2.29	10.88	6.22	0.95	2.91	0.53	5.33	3.31	3.77

* MISSING DATA, VALUES SHOWN ARE INTERPOLATED FROM 2 OR 3 NEARBY STATIONS.
** INCLUDES 2 OR MORE DAYS OF CUMULATIVE RAINFALL IN ORIGINAL CLIMATOLOGICAL DATA.

APPENDIX B (CONTINUED)
TROPICAL STORM RAINFALL PER STORM

CITY	SEPT. 6- 7 1969	OCT. 1- 4 1969	SEPT. 13-15 1970	SEPT. 26-27 1970	AUG. 10-12 1971	SEPT. 4- 6 1972	JUNE 24-28 1974	OCT. 6- 7 1974	JUNE 26-27 1975	AUG. 17-19 1976
ARCADIA	0.62	4.17	0.85	0.23	0.79	0.25	8.15	0.05	0.00	2.57
AVON PARK	0.07	3.12	0.68	0.22	1.29	0.17	10.38	0.05	0.52	2.17
BARTOW	0.00	2.64	0.55	0.09	0.74*	0.07	5.73	0.01	0.02	2.00
BELLE GLADE	0.15	1.18	0.82	0.42	0.00	0.00	5.23	0.54	0.64	2.94
EVERGLADES CITY	0.36	1.31	0.75	0.15	2.66	0.50	4.81*	0.01	0.00	1.28
FELLSMERE	0.79*	2.39	1.60*	0.56*	0.94	0.09	3.51*	1.38*	0.37	1.60
FORT LAUDERDALE	0.70	1.25	1.56	0.84	0.65	0.30	0.61	2.05	0.62	9.81
FORT MYERS	0.15	3.92	4.47	0.02	2.11	0.00	9.61	0.02	0.00	2.78
FORT PIERCE	1.20	1.07	1.58	0.36	0.18	0.00	4.02	2.05	0.00	0.14
HOMESTEAD	0.17	1.32	0.66	0.76	1.06	1.13	1.17	0.13	2.56	4.67
ISLEWORTH	1.00	4.10	0.27	0.00	0.22	0.00	9.37	0.22	0.52	1.08
KISSIMMEE	0.76	2.77	0.32	0.10	0.18	0.00	7.61	0.24	0.74	1.06
LA BELLE	0.14	1.58	0.06	0.17	1.50	0.00	10.06	0.01	0.12	2.15*
MIAMI	1.88	1.08	5.58	0.55	0.28	1.05	1.20	1.38	0.32	3.89
MOORE HAVEN	0.11	3.99	0.23	0.07	1.74	0.00	6.42	0.50	1.25	1.52
OKEECHOBEE	0.37	2.59	1.63**	0.76**	0.30	0.00	4.79*	0.71	0.01	0.88
ORLANDO	0.39	3.05	0.41	0.00	0.18	0.01	10.76	0.41	0.02	0.46
PUNTA GORDA	0.29	1.91	0.27	0.15	2.22	0.02	12.44	0.02	0.12	0.62
WEST PALM BEACH	1.33	1.01	2.46	0.22	0.15	0.02	1.89	4.39	0.09	2.93

* MISSING DATA, VALUES SHOWN ARE INTERPOLATED FROM 2 OR 3 NEARBY STATIONS.
** INCLUDES 2 OR MORE DAYS OF CUMULATIVE RAINFALL IN ORIGINAL CLIMATOLOGICAL DATA.

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Donald Brandes received his B.A. in geography at the University of Florida in 1968, secondary school teacher certification at the University of Alberta in 1970, and M.A. in geography with a specialization in cartography at the University of Calgary in 1975. Between 1970 and 1975, he taught in high schools in North Bay, Ontario, and Vernon, British Columbia, and from 1975 to 1977 he was Graphics Coordinator for the Planning Division of the Department of Community Development, City of Gainesville, Florida. From 1978 to 1981 he taught courses in the Department of Physical Sciences and the Department of Geography at the University of Florida as a half-time graduate teaching assistant.

Between 1975 and 1981 he has published seven articles in professional journals, presented papers at professional meetings, and produced numerous illustrations for publication, including a cover design for the AAG Specialty Group on Marine Geography. Mr. Brandes is a member of the Association of American Geographers, the American Congress on Surveying and Mapping, the Canadian Cartographic Society, The Florida Society of Geographers, Gamma Theta Upsilon (national professional geographic fraternity), the Guild of Natural Science Illustrators, and the Southeastern Division of the Association of American Geographers.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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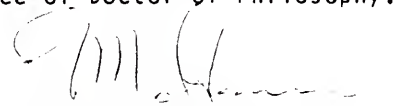

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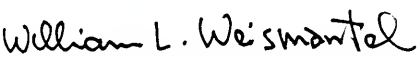

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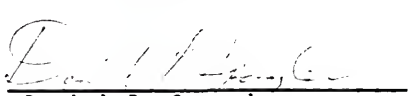

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This dissertation was submitted to the Graduate Faculty of the Department of Geography in the College of Liberal Arts and Sciences and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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